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Abstract. Fire hazard studies have shown that lightning is a major threat to petroleum storage facilities, especially floating roof tanks (FRT) due to the risk of lightning-induced fires which may ultimately result in tank boil over, and an increased risk of the fire spreading to adjoining facilities. Lightning is a natural occurrence with scientific attributes that have been studied for decades towards mitigating lightning-related hazards. The probability of a direct lightning strike to various points on a FRT can be estimated by applying the dynamic electro-geometrical model (DEGM) using numerical techniques, and this provides information on the high-risk lightning-strike points on the FRT. This numerical approach involves surface discretization resulting in millions of meshed points in some cases, both on the structure and the surrounding space. This requires a lot of computer resources, and the simulation is slow to compute. In this study, simple and easy to compute equations were developed and hereby proposed as alternatives to numerical DEGM by applying analytical equations directly from first principles. The result confirms the susceptibility of the shell's rim region to direct lightning strikes with 90.61% probability of a direct strike for a 20 m high tank and 88.58% for a 15 m high tank with 60 m in diameter. The results show close approximations to the numerical model and also reveals the effects of the discretization size on the accuracy of the numerical approach, while also reducing the computation time from several hours to a few minutes.

1. Introduction

A top-notch risk identification process for guiding design, operational and maintenance activities in the oil and gas industry is required to ensure adequate safety of personnel and equipment. Risk analysis helps to identify potential hazards so that mitigative actions can be deployed to prevent occurrence. In the petroleum and chemical facilities, residual risk must not be higher than the normally acceptable risk level after deploying controls. Risk evaluation helps to identify the level of hazardous occurrences by applying analytical techniques which can be qualitative or quantitative in nature [1]. It is essential to ensure that all failure points are identified to guarantee the integrity of the risk-control measures deployed [2] in compliance with relevant industry standards and code of practice. Floating roof tanks (FRTs) are vital for storing petroleum-related products and are typically installed in the open, exposed to environmental elements such as lightning strikes which portend a significant level of fire risk. According to the popular maxim, commonly referred to as Murphy's law which states that "anything that can go wrong will go wrong" therefore, it becomes imperative to develop an in-depth understanding of lightning interactions with crude oil storage facilities, and in particular, the floating roof tank.

Operational defects and errors aggravate the risk of a lightning-induced and other FRT fires and associated damages. Errors such as tank overfilling, overriding automatic control systems, excessive fast filling of tanks which results in the build-up of static charges [3], faulty or delayed maintenance and replacement of vital safety and operation equipment, poor vapour control system, poor hot-work management, design failures [4], inadequate fire detection and firefighting systems, high vapour pressure, sinking roof [5] which may be due to snow [6], etc. The use of shunts for bridging electrical discontinuity between the FRT's shell and the roof is ineffective due to observed sparking at the shell-shunt interface at various lightning current values. Studies such as Hu and Liu [7] recommends that shunts should not be installed on FRT's because both shunts and mechanical seals act as ignition sources within the flammable vapour space of the rim-seal region under lightning strike conditions. Therefore, this demands an improved understanding of high-risk points on FRTs towards designing a conventional lightning protection system for FRTs.

Indirect lightning strikes may constitute a risk to FRT due to induced voltages and transient currents especially when the grounding and bonding systems are inadequate, but of more significance in terms of the risk of fire are directs strikes to FRTs. According to [8] as reported by Liu, et al. [9] electric field strength of 1.15 kV/m around sensitive devices can result in damage. Liu, et al. [9] emphasized that indirect lightning strikes to the ground of current magnitudes greater than 30 kA within a distance of 1200 m to the FRT can constitute a risk to sensitive electronic devices due to the lightning radiated impulse power. For large FRTs at 30 kA, a dangerous distance of 30 m was determined within which an electric field of 200 kV/m can be induced in the tank shell and this can result in the breakdown and ignition of flammable vapours within the FRT. The effects of indirect lightning strikes can be controlled by using surge protective devices on sensitive electronic and electrical devices on the FRT. This position is further supported by Sueta, et al. [10] which emphasized that the impact of direct strikes on storage tanks and hot spot formation should be the main research focus.

Lightning creates a significant challenge for oil and gas storage facilities due to the risk of lightning-induced fires [11]. It is vital to eliminate or at least reduce sources of losses to ensure the rational use of natural resources. Crude oil, gas condensate, and gasoline are typically stored in steel floating roof tanks (FRTs). FRT helps to stabilize the crude and limit vapour pressure, but FRTs are susceptible to lightning-related fires, especially at the rim-seal region. A fire hazard study performed in China [12] on 107 FRTs revealed that 65, i.e. 61% of these fires were due to lightning strikes [13-15]. Currently, there is no air termination design for FRT in lightning protection standards. Designing a conventional lightning protection system (LPS) for FRT requires an adequate understanding of the variations in the exposure of various parts of a FRT to lightning strikes. This can be achieved by developing a simulation to analyse the probability of a direct strike to a FRT. The numerical simulation creates a challenge because it is slow, and take days to compute in some cases, even on computers with good specification, and this creates a heavy demand on computer resources [16]. This study presents an equivalent, accurate, and novel analytical computation resolved down to simple equations for determining the probability of a lightning strike to various parts of a FRT without the need for any slow and hard to model numerical simulation.

The numerical computation of the probability of a lightning strike to a FRT can be performed by applying the concept of the dynamic electro-geometrical model (DEGM) [17]. In the DEGM model, the surface of the FRT, the ground, and the space area around the tank are discretized into meshes for determining the probability of a strike to each meshed point using the lightning probability density function [16, 18]. This may require millions of iterations to compute in some cases, which makes it slow in generating results. Also, there is a need for a programming skill to implement the intricate model. Alternatively, a simplified analytical technique using simple equations that are based on the dimension of the FRT and space points as a function of increasing striking distance radius (*r*) can be developed as proposed in this study with a focus on FRT.

2. Methodology

In the numerical model, an attractive volume around the structure of interest is defined as the volume from which lightning can strike the structure. Surface layers within this volume at different rolling sphere radii (i.e. striking distance) are meshed to create surface points. In the analytical method proposed in this study, geometrical equations were developed to define the surface areas of orientation points as a replacement for the surface meshing approach. The analysis was performed separately for the three unique parts of the FRT. The cylindrical sidewall which covers all surface area on the FRT's shell from the ground to just below the top rim, the rim edge which defines the circular rim at the topmost height of the tank shell, and the roof area which covers the surface of the tank's floating roof. Collection volumes were developed for each of the three as discussed in sections 3.1, 3.2 and 3.3 respectively.

The three parts of the FRT as previously classified have their unique lightning strike collection volume or orientation point surfaces from which a lightning strike can emerge and strike them. This collection of surface areas for each of the three parts as a function of striking distance r in m are hereafter referred to as A_{roof} for the floating roof area, A_{rim} for the top rim-edge of the tank cylinder, and A_{wall} for the cylindrical sidewall. For the sidewall and the rim edge, the computation was performed for a unit sectional area defined by a span θ_1 of $1/R$ radians, where R is the radius of the FRT. Therefore, the sectional result must be multiplied by the circumference of the cylinder. Analytical equations using these concepts were developed to describe the three surface areas. These equations were incorporated into an integral equation modulated by the lightning striking-distance based probability density function PDF(r) to generate the probability modulated lightning collection volume (PMCV) for a FRT of height h.

The probability density function (PDF) in terms of the striking distance (r) is defined in Equation 1.

$$PDF(r) = 0.9 \times \frac{e^{\dfrac{-\ln 2 \left[\dfrac{\left(\dfrac{r}{10}\right)^{\frac{1}{0.65}}}{\mu_n}\right]}{2\sigma_n^2}}}{0.65\sigma_n\sqrt{2\pi}\times r} + 0.1 \times \frac{e^{\dfrac{-\ln 2 \left[\dfrac{\left(\dfrac{r}{10}\right)^{\frac{1}{0.65}}}{\mu_p}\right]}{2\sigma_p^2}}}{0.65\sigma_p\sqrt{2\pi}\times r} \tag{1}$$

In Equation 1 and the subsequent analysis, the following variables are defined as follows:
  R is the radius of the FRT in m
  h is the height of the FRT in m
  r is the striking distance in m
  σ is the standard deviation and μ is the median value of the lightning current distribution.
  Subscripts n and p represent negative and positive lightning current components, respectively, they stand for the standard deviation and the median values [16].

3. Analytical computation of the DEGM for FRT

3.1. The FRT's sidewall

The collection volume for the sidewall of the FRT is depicted in Figure 1, the striking distance at any point and at any height (h) on the sidewall extends laterally by distance h, and this gives a linear relationship between the height of the point under consideration on the sidewall and the effective striking distance.

An analytical equation was developed using the concept of a unit sectional collection area (A_{wall} / unit), as shown in Figure 2. For a unit sectional area for the circumferential sidewall, we have the following analysis:

  Striking distance (r) $= h$ (2)

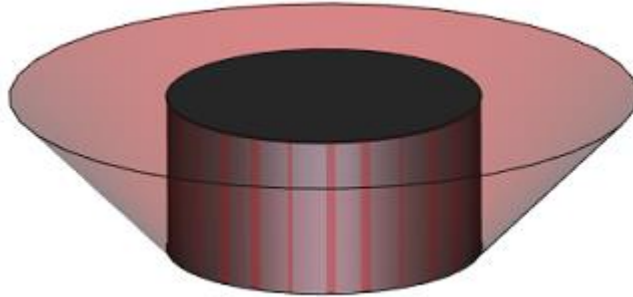$$\text{Effective radial span } (R^*) = R + h = R + r \tag{3}$$

Figure 1. Lightning strike collection volume for the cylindrical sidewall of the FRT

Considering a unit 1 m arc interval on the FRT's circumference, we define a unit angular span in radian as θ_{unit}.

$$\theta_{unit} = \frac{2\pi}{2\pi R} = \frac{1}{R} \tag{4}$$

The effective radial arc as function of radius $A(r) = \dfrac{R^*}{R} = 1 + \dfrac{r}{R}$ (5)
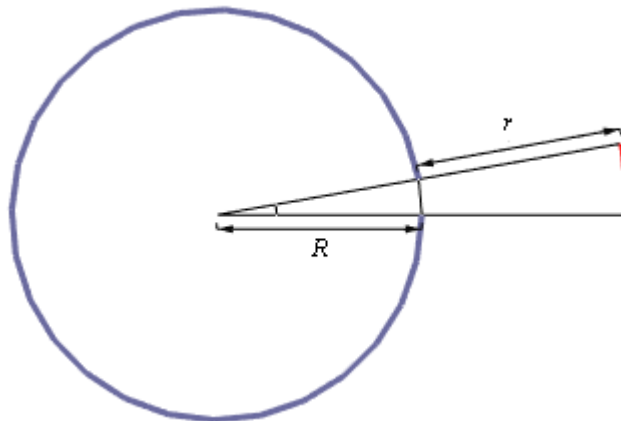

Figure 2. The side flash area for a unit sectional area of span θ_{unit} of the cylindrical FRT wall

The equivalent lateral collection area for a unit sectional area on the FRT at any height (h) is

$$A_{wall} = \int_{r=0}^{r=h} PDF(r) \cdot \left(1 + \frac{r}{R}\right) dr \tag{6}$$

We now consider this lateral sectional unit vertically from the base of the FRT that is the ground to the reference height.

$$PMCV_{wall} \text{ / unit} = \sum_{r=0}^{r=h} \int_{r=0}^{r=h} PDF(r) \cdot \left(1 + \frac{r}{R}\right) dr \tag{7}$$

The probability-weighted lightning collection volume in m² for the whole cylindrical FRT's sidewall up to any height (h) is defined as

$$\text{PMCV}_{\text{wall}} = 2\pi R \times \text{PMCV}_{\text{wall}} \,/\, \text{unit} \; = 2\pi R \sum_{r=0}^{r=h} \int_{r=0}^{r=h} PDF(r) \cdot \left(1 + \frac{r}{R}\right) dr \tag{8}$$

3.2. The FRT's rim edge

The collection volume of the rim edge of the FRT and the roof area are depicted in Figure 3. The volume for the rim edge extends from the tip of the tank shell at its highest height outwards forming a hollow section. The unit sectional collection volume is applied to evaluate the probability of a lightning strike to the rim edge of the FRT. The span of the collection volume from the rim edge of the FRT increases with increasing height upwards to infinity. Considering a unit 1 m arc interval along the FRT's rim edge, we develop a sectional unit as depicted in Figure 4.
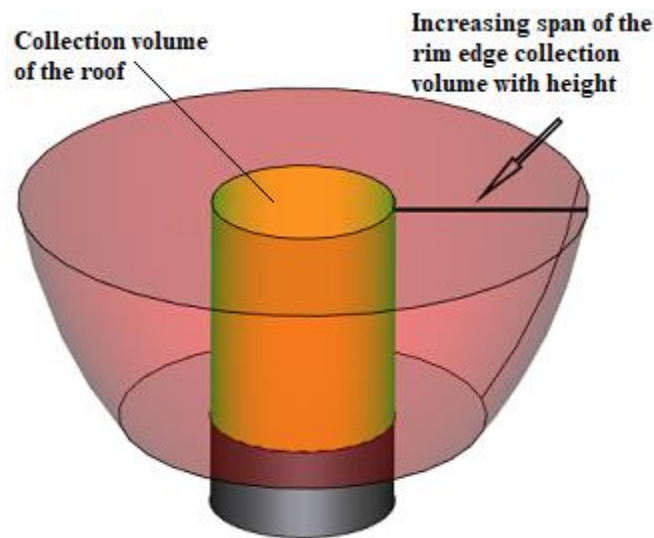

Figure 3. Lightning strike collection volume for the rim edge and the inner floating roof

For a striking distance of rolling sphere radius (r), for a lateral angular span of θ_1, and vertical span of θ_2, a curved surface area is generated as depicted in Figure 4. All angles are in radians.

$$\theta_1 = \theta_{unit} = \frac{2\pi}{2\pi R} = \frac{1}{R} \tag{9}$$

$$\theta_2 = \cos^{-1}\left(1 - \frac{h}{r}\right) \tag{10}$$

Where h is the topmost height of the FRT.

Developing an integral equation to express the surface area of the curved section in Figure 4 will give a very complex and difficult-to-solve equation. A simplification was applied to avoid this complexity, by flattening this curved section to generate a flat planar surface, as shown in Figure 5.

There are two sections in this computation. First, we consider collection surface from the rim edge of the FRT to height (h) of the FRT above the rim edge, and then we compute from h to infinity (up in the sky).
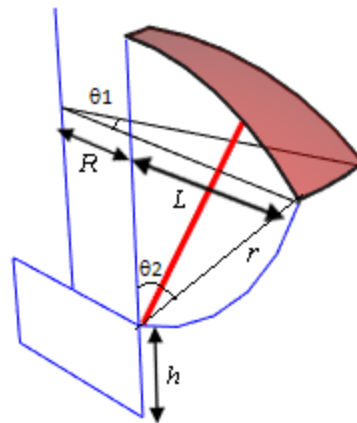
Figure 4. Lightning strike collection surface for a unit sectional area of the FRT's rim edge
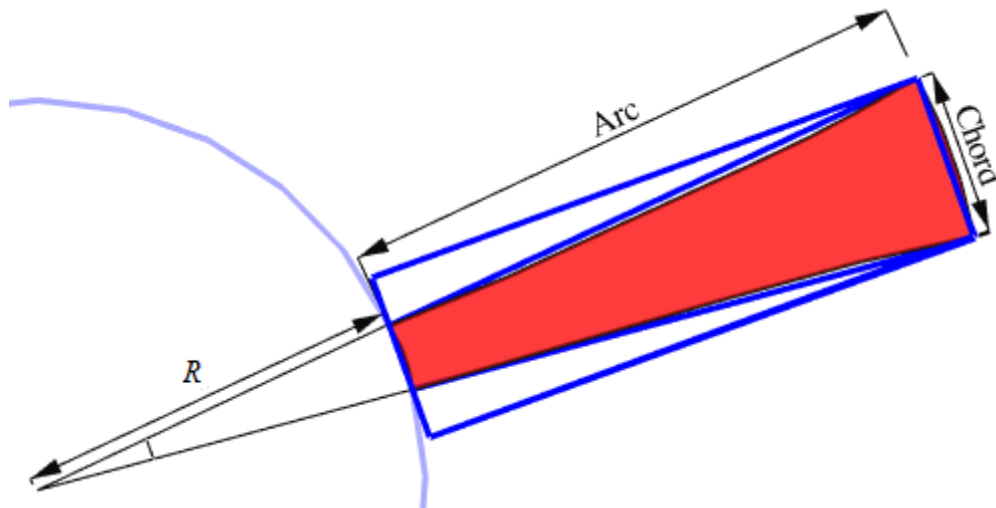

Figure 5. Flattened equivalent area for the sectional area defined by a span θ_1 of the tank rim edge

For striking distance $r = 0$ to h above the rim edge, we have the following analysis. There are two border lengths, one is on the FRT's cylinder, and the second at the exterior end of the collection surface, as shown in Figure 5.

$$BorderA = 2R\sin\left(\frac{1}{2R}\right) \tag{11}$$

$$BorderB = 2(r+R)\cdot\sin\left(\frac{1}{2R}\right) \tag{12}$$

The flattened arc length can be determined as follows:

$$ArcA = \frac{\pi r}{2} \tag{13}$$

The horizontal length of the section is determined as follows:

$$LengthA = ArcA \times \cos\left(\frac{1}{R}\right) \tag{14}$$

The effect of using a flattened surface to model the area of the curved surface can be approximated as defined in Equation 15 using a correction factor of 0.725 based on analysis in FreeCAD 3D software. This compensates for the distortion caused by straight line approximation of curves.

$$A_{rim1} = \left(LengthA \times BorderB \right) - \left(\frac{BorderB - BorderA}{2} \times 0.725 \times LengthA \right) \tag{15}$$

The equivalent collection area for a unit sectional area of the rim edge on the FRT from 0 to h above the rim edge is:

$$PMCV_{rim} / unit \Big|_{0\ to\ h} = \int_{r=0}^{r=h} PDF(r) \cdot A_{rim1}\ dr \tag{16}$$

The probability-weighted lightning collection volume in m^2 for the whole cylindrical FRT's rim edge up to height (h) above is as follows.

$$PMCV_{rim} \Big|_{0\ to\ h} = 2\pi R \times PMCV_{rim} / unit \Big|_{0\ to\ h} = 2\pi R \int_{r=0}^{r=h} PDF(r) \cdot A_{rim1}\ dr \tag{17}$$

For striking distance $r = h$ to ∞ above the rim edge, we have the following analysis. The chord length BorderB is redefined as BorderC in this case.

$$BorderC = 2(L+R) \cdot \sin\left(\frac{1}{2R} \right) \tag{18}$$

The flattened arc length is also redefined as follows:

$$ArcB = r\theta_2 \tag{19}$$

The horizontal length of the section is determined as follows:

$$LengthB = ArcB \times \cos\left(\frac{1}{R} \right) \tag{20}$$

The effect of using a flattened surface to model the area of the curved surface can be approximated as defined in Equation 21 using a correction factor of 1.02 based on the analysis in FreeCAD software.

$$A_{rim2} = \left(LengthB \times BorderC \right) - \left(\frac{BorderC - BorderA}{2} \times 1.02 \times L \right) \tag{21}$$

The equivalent collection area for a unit sectional area of the rim edge on the FRT from h to infinity above the rim edge is:

$$PMCV_{rim} / unit \Big|_{h\ to\ \infty} = \int_{r=h}^{r=\infty} PDF(r) \cdot A_{rim2}\ dr \tag{22}$$

The equivalent collection area for a unit sectional area of the rim edge on the FRT from 0 to infinity above the rim edge is:

$$PMCV_{rim} / unit = PMCV_{rim} / unit \Big|_{0\ to\ h} + PMCV_{rim} / unit \Big|_{h\ to\ \infty} \tag{23}$$

The probability-weighted lightning collection volume in m^2 for the whole cylindrical FRT's rim edge from h up to infinity is defined as follows.

$$PMCV_{rim} \Big|_{h\ to\ \infty} = 2\pi R \times PMCV_{rim} / unit \Big|_{h\ to\ \infty} = 2\pi R \int_{r=h}^{r=\infty} PDF(r) \cdot A_{rim2}\ dr \tag{24}$$

The total PMCV for the rim edge of a floating roof tank from 0 to infinity is defined as:

$$PMCV_{rim} = PMCV_{rim} \Big|_{0\ to\ h} + PMCV_{rim} \Big|_{h\ to\ \infty} \tag{25}$$

3.3. The FRT's roof
The collection volume of the roof of the FRT is depicted in Figure 3. The volume for the roof is cylindrical, extending from the surface of the roof (0 m) up to infinity (in the sky). The unit sectional area is also applied in this case to evaluate the probability of a lightning strike to the roof of the FRT at its highest vertical position.

Considering a unit m^2 area of the floating roof, the effective collection surface area is:

$$A_{roof} = \int_{r=0}^{r=\infty} PDF(r)\, dr \tag{26}$$

For the whole floating roof, we compute as follows:

$$PMCV_{roof} = \pi R^2 \int_{r=0}^{r=\infty} PDF(r)\, dr \tag{27}$$

Floating roof tanks are generally about 10 m to 20 m in height. To provide an extended range, the analytical computation in this study was developed for various FRT heights ranging from 1 m to 40 m. The total PMCV for the floating roof tank as a whole will be calculated by summing the PMCV$_{wall}$, PMCV$_{rim}$, and PMCV$_{roof}$. This value will then be applied to determine the percentage contribution of each component.

4. Results and discussion

The unit sectional lightning collection area was computed for a case study floating roof tank of radius 30 m with tank height variations from 1 m to 40 m. Figure 6 shows the PMCV for a unit sectional collection area according to Equation 6. The plot highlights the effects due to negative lightning alone, positive lightning alone, and the overall effect when modified by PDF(r) as defined in Equation 1. Figure 7 displays the PMCV for a unit section of the rim edge of a FRT at its apex height with respect to Equation 23, while Figure 8 shows the PMCV for a unit sectional area of the roof of a FRT according to Equation 26. The performance of the analytical model was verified by carrying out DEGM numerical simulations for a FRT of radius 30 m. Two tank heights were considered, and these are 15 m and 20 m. This would enable a direct comparison of the results of both approaches.

In the numerical computation, a discretization of 1 m was applied radially along the length of the roof, and vertically along the height of the wall. The implication of this is that a 1 m radial surface is lost at the edge of the floating roof because this point represents the tank rim edge. Likewise on the tank cylindrical wall or shell, starting from the ground upwards, a 1 m area before the apex of the tank height is also lost because this point also represents the tank rim edge. The smaller the discretization size (e.g. 0.25 m), the lower the area lost in the numerical computation, but the longer the simulation time. The effect of this numerical error on the result will be demonstrated by computing the analytical result twice, i.e. without and with a reduction of 1 m in roof radius i.e. $R-1$ m which gives $[\pi(R-1)^2]$ for the roof area and a reduction of 1 m in the cylindrical wall height (0 to $h-1$ m). The summary of the analytical results is presented in Table 1 for the 15 m high FRT and in Table 2 for the 20 m high FRT. The analytical result considering the effect of the numerical discretization error is termed analytical 1, while the best result that depicts reality without the effect of the numerical error is referred to as analytical 2 in Tables 1 and 2.

Table 1. The lightning strike probability in percentage to various sections of the 15 m FRT

Tank Section	Numerical (%)	Analytical 1 (%)	Analytical 2 (%)
Cylindrical Wall	0.016	0.014	0.019
Rim Edge	88.645	88.578	87.870
Roof	11.339	11.408	12.111
Total	100.000	100.000	100.000

Table 2. The lightning strike probability in percentage to various sections of the 20 m FRT

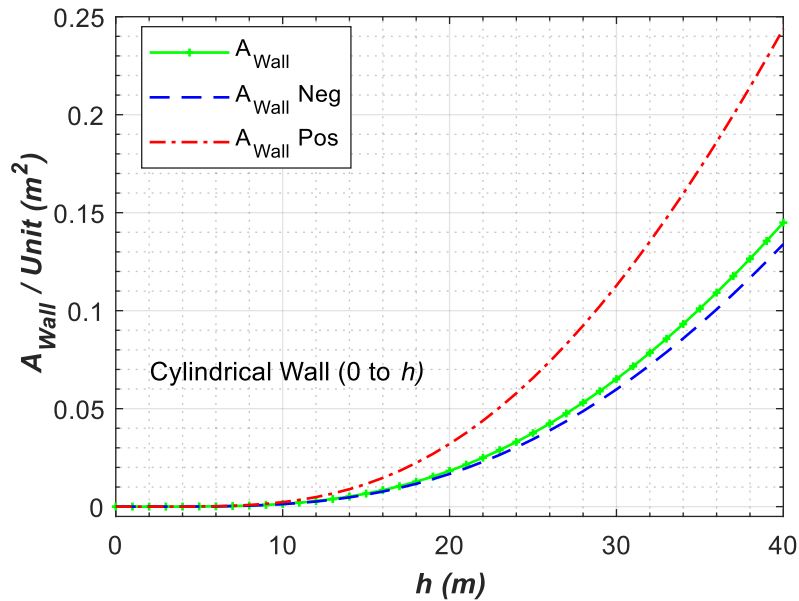| Tank Section	Numerical (%)	Analytical 1 (%)	Analytical 2 (%)
Cylindrical Wall	0.052	0.047	0.059
Rim Edge	90.586	90.610	90.009
Roof	9.362	9.343	9.932
Total	100.000	100.000	100.000

Figure 6. Collection area for a unit section of the cylindrical wall at a point with height *h*
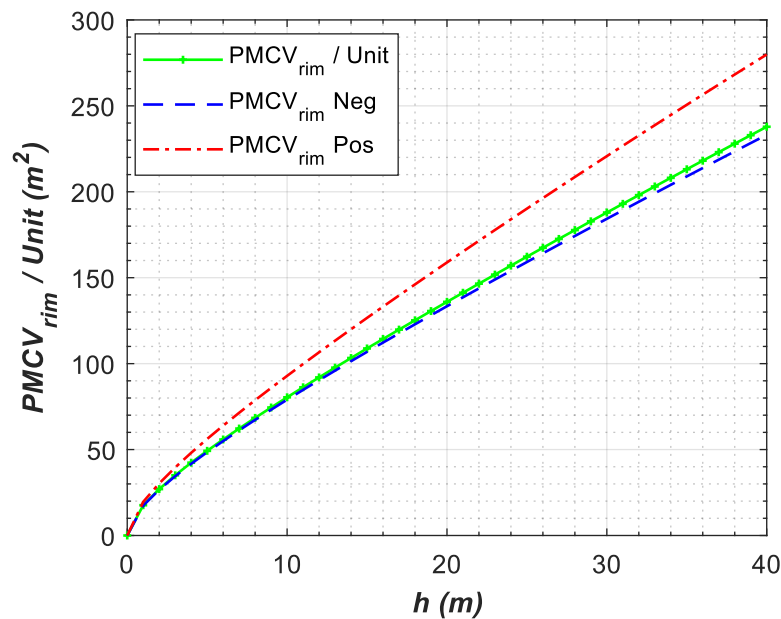

Figure 7. PMCV for a unit section of the rim edge of a FRT of maximum height *h*

The results in Tables 1 and 2 show that the analytical results with (analytical 1) and without (analytical 2) the effects of the numerical discretization are reasonably close to the numerical results. Also, analytical 1, which considers factors due to the 1 m discretization effect of the numerical modelling, gave the closest values to the numerical results. The computation of the integrals and graphs was achieved in less than 90 seconds as compared to more than 20 hours using numerical DEGM simulations set up to identify strikes to the FRT from strikes to nearby grounds. The analytical equations performed accurately well for the cases considered as compared to the numerical result.
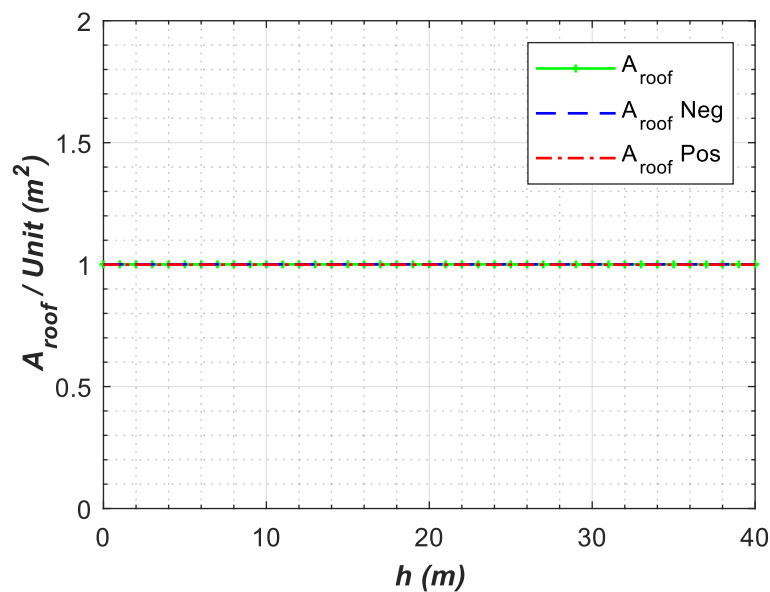
Figure 8. Collection area for a unit sectional area of the roof of a FRT

Due to typical errors associated with numerical simulations, as they are often an approximation of the true result, within the limits of analytical approximations, the analytical model is more accurate than the numerical result obtained using the DEGM. Hence, simple, easy to use and accurate equations are now available for estimating the probability of a lightning strike to various parts of a cylindrical tank, towards enabling the design and implementation of a safe and effective lightning protection system.

5. Conclusions

Lightning is a dynamic phenomenon, and although its attributes can be studied, its behaviour and likelihood of strike cannot be predicted with 100% accuracy. This study applies the dynamic electro-geometrical model to evaluate the probability of lightning strikes to various parts of a floating roof tank using both numerical and analytical methodologies. The result shows that, while the two methods gave reasonably close results, the analytical method is extremely fast and can be computed in less than two minutes as compared to the numerical model that runs for several hours. This gives the analytical model a significant time advantage. The result of the analysis confirms the susceptibility of the shell's rim region to direct lightning strikes with 90.61% probability of a direct strike for a 20 m high tank and 88.58% for a 15 m high tank with a 60 m diameter. The analysis also shows that a numerical discretization error is introduced when the numerical method is applied, and this error reduces with smaller discretization size.

As an extension of this study, using the results of the analytical computation, data fitting techniques can be applied to the resulting dataset for developing more simple quadratic or power equations for the PMCV values as a function of the FRT's height (h). Also, a mimic of the slow numerical model can be achieved by using the analytically computed per unit PMCV values. This can be used to develop a point-wise computation of the probability of lightning strikes which will be equivalent to a discretization of 1 m × 1 m using the numerical approach. The advantage of such a mimicked model is that the analytical approach only provides the total probability of strikes in values. The results of the mimicked model can be computed in a few minutes and also used to generate a 3D colour-coded image of the probability of a lightning strike in percentage for the seemingly meshed points of the FRT.

Acknowledgement

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