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A novel method to design water spray cooling system to protect floating roof atmospheric storage tanks against fires

*Iraj Alimohammadi [1], Farshad Nourai [2], Mohammad Javad Daryalaal [3], Amir Masood Ghasemi *[4]*

1) Department of Occupational Health Engineering, School of Public Health, Iran University of Medical Science, Occupational Health Research Center
2) Aftab Imen Parto Consulting Engineers Ltd
3) Subsidiary HSE Department at National Iranian Oil Company
4) Department of Occupational Health Engineering, School of Public Health, Tehran University of Medical Science

**Author for Correspondence: journalqasemi@gmail.com*

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ABSTRACT
Hydrocarbon bulk storage tank fires are not very common, but their protection is essential due to severe consequences of such fires. Water spray cooling system is one of the most effective ways to reduce damages to a tank from a fire. Many codes and standards set requirements and recommendations to maximize the efficiency of water spray cooling systems, but these are widely different and still various interpretations and methods are employed to design such systems. This article provides a brief introduction to some possible design methods of cooling systems for protection of storage tanks against external non-contacting fires and introduces a new method namely “Linear Density Method” and compares the results from this method to the “Average Method” which is currently in common practice. The average Method determines the flow rate for each spray nozzle by dividing the total water demand by the number of spray nozzles while the Linear Density Method determines the nozzle flow rate based on the actual flow over the surface to be protected. The configuration of the system includes a one million barrel crude oil floating roof tank to be protected and which is placed one half tank diameter from a similar adjacent tank with a full surface fire. Thermal radiation and hydraulics are modeled using DNV PHAST Version 6.53 and Sunrise PIPENET Version 1.5.0.2722 software respectively. Spray nozzles used in design are manufactured by Angus Fire and PNR Nozzles companies. Schedule 40 carbon steel pipe is used for piping. The results show that the cooling system using the Linear Density Method consumes 3.55% more water than the design using the average method assuming a uniform application rate of 4.1 liters per minute. Despite higher water consumption the design based on Linear Density Method alleviates the problems associated with the Average Method and provides better protection.

Key words: Storage Tank, Cooling System, Fire Protection, Spray System, Spray System Design, Tank Fire

INTRODUCTION
Bulk storage tanks containing hydrocarbons are prone to huge fires. Although such fires are rare, the consequences are catastrophic. The size and impact they create on the tank owner could threaten the survivability of the company and lead to bankruptcy. Fires in Cataño oil refinery and Buncefield oil depot are two fires involving several tanks which caused major destruction and created a national crisis. Due to huge volume of liquids stored the extinguishment can be a challenge. If extinguishment of the fire on a tank is not possible for protecting adjacent tanks is essential.

Water spray cooling systems can reduce damages to the tank on fire and reduce the risk of escalation and delay involvement of adjacent tanks [1, 2].

Such systems have been designed and installed in many oil companies, but they aren’t efficient and in some cases not operable. Some reasons for that are poor design of distribution piping system, inappropriate spray nozzle selection, failing to observe tank geometry, designing tank protrudances irrespective of cooling system and vice versa.

In non-contacting fires, the majority of heat is transferred to an adjacent tank by thermal radiation [1]. Investigation by the American Petroleum Institute shows that 6% of fires are caused by radiation [3]. In this article, the design of cooling system for protection of floating roof tanks [4, 5] containing crude oil against non-contacting fires from a similar adjacent tank using a new method is studied. The new method first determines the water application rate based on incident radiation. Then the Linear Density Method is used to apply the derived application rate in the previous step and for the distribution system. The design removes the problems associated with previous methods. For the matter of acquaintance at the first major design strategies are briefly discussed. To give perspective the results of this new design strategy is compared to another more common strategy of design that uses the average method to distribute water.

For the cooling system to be efficient some considerations in the design of water distribution, piping system and tank protrudances need to be observed: The number of feed pipes depends on the number of wind girders (stiffening ring) on the shell of the tank. Due to smaller plate thickness of the tank upper course and higher incident radiation application of cooling water to the shell above walkway is deemed very necessary [6]. This idea is also backed by thermal radiation modeling. Protection of this area of shell of floating roof tanks is not common in current design practice mostly because the piping restricts easy access around the top of the tank. The positioning of feed pipes for the cooling system shall be in a way that there is some space between the tank components and the spray nozzle/feed pipes. The orientation of the spray nozzle on feed pipes shall be such that no dry spots form under the wind girder. It may be necessary to install the nozzles with some deflection from the vertical. Inappropriate pipe sizing could lead to inappropriate pressure and inadequate water discharge at most remote nozzles. It's highly important to keep pressure difference between the closest and farthest nozzle to a minimum. This ensures a regular discharge curtain and uniform water distribution from the spray nozzle. Use of triangular support plates for top walkway of the tank should be avoided since they hinder the spray curtain and results in non-uniform water film and dry spots on tank wall. It is best to use slender members such as bars or angle iron to support the walkway. The stairway shall be installed so that the water film on the tank reaches the area of shell below the stairway. If this is not possible in a separate branch of pipe shall be provided to supply water to those sections.

MATERIALS AND METHODS

The piping used for the design of cooling system is schedule 40 carbon steel pipes which are commercially available. Spray nozzles with k-factors of 25, 45 and 65 manufactured by Angus Fire Company are used for areas below wind girder (top walkway). For the portion of the tank shell above walkway PNR short body nozzle with a k-factor of 7.16 is used. Modeling of incident radiation on adjacent tank is carried out using version 6.53 of DNV PHAST software that is widely used for that purpose. The distribution piping hydraulic calculation and sizing is carried out using version 1.5.0.2722 of SUNRISE PIPENET software which is standard software for hydraulic calculations.

Design Strategy Outline

The design of a cooling system depends on the type protection intended which in turn determines the water application rate. The piping system is then designed to deliver the required water density with most efficiency. Fig. 1 demonstrates the outline of designing procedure.

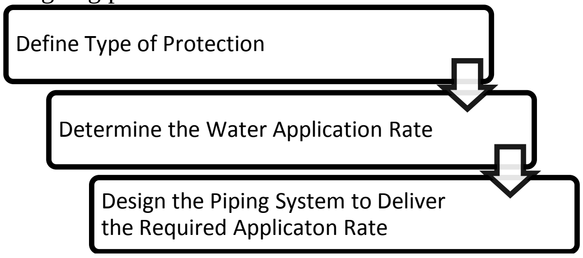

Fig. 1: Cooling System Design Steps

Type of Protection

Design objectives for cooling systems for storage tanks are divided into three major categories:

1) To protect a tank against internal fires: this type of protection is complicated because the fire is in contact with the internal surface of the shell and water is applied to the external shell surface. In any case the application of cooling water for protection of a tank against such fires is not studied and standards provide no recommendations for water application rates or other system parameters.

2) To protect a tank against external contacting fire: two different types of fires is possible for external contacting fires. One is pressurized jet fire and the other non-pressurized fire due to spills. The former requires relatively higher water application rates to dissipate heat from a fire.

3) To protect a tank against external non-contacting fire: the effect of thermal radiation from a fire on adjacent tanks can be disastrous. Thermal radiation could damage the adjacent tanks or even set them on fire. To protect adjacent tank cooling water is applied to the exterior shell. The water is used to absorb the heat incident on the tank and reduce the heat input to the tank and diminish the risk of escalation [2, 4].

Water Application Rate

If a water film of minimum thickness is maintained, the metal surface temperature can continue to a certain value [7]. Water application rate is closely linked to the extent of exposure and type of protection intended [8, 9]. For a particular protection there are three major strategies to determine water application rate:

1) According to values provided by codes and standards: Variation between codes is wide and sometimes contradicting so that no clear conclusions can be drawn. Table below lists some recommended water application rates used in different codes and countries:

2) According to radiation incident on the target to be protected: The precise water requirement mainly depends on the intensity of radiated heat, the absorbance of irradiated surface, the effect of wind

on any flame pattern and the separation distance of equipment radiation source [8]. The required amount of water can be calculated on the basis of film thickness and incident radiation on tank. The method first determines the total incident radiation from the adjacent fire. Then the maximum permissible radiation level for the tank is derived using one of three methods:

a) Critical Temperature of shell steel plates: This criteria is not suitable for cooling system design since the auto ignition of the flammable liquid is reached long before the critical temperature of the steel. Resources provide different values for critical temperature of steel [3, 14].

b) The auto ignition temperature of storage tank contents: This is a sound criterion to determine the application density of cooling water. Using this method, the amount of permissible heat input and hence water density can be determined.

c) Recommended values in standards and literature: So many authors and literature have studied the permissible heat flux limits for storage tanks. Model Code of Safe Practice, Part 19 recommends a value of 8 kW/m^2 for storage tanks [6, 8].

Table 1: Water Density for Protection of Tanks

Country Name	**Development Unit**	**Water Intensity Requirement (lit/min/m²)**		**Reference**
		Fire Tank	**Adjacent Tank**	[10]
USSR	National Standards	2.8	1.1	[10]
USA	NFPA	8.15	-	[10]
	NFPA 15	10.2	-	[11]
	ESSO Engineering Company	3.66	-	[10]
	API 2030	10.2	4.1	[12]
UK	Fire Protection Association	9.8	-	[10]
	IP 19	10	2	[8]
France	National Standards	5-15	-	[10]
Japan	Standard Fire Insurance Company	10	-	[10]
China	National Standards	2.5 (Floating Roof Tank) 2 (Fixed Roof Tank)	2	[10]
Iran	Iranian Petroleum Standards	10.2	-	[13]

The difference of the incident and permissible radiation determines the amount to be absorbed by water film.

Distribution Piping

Fig. 2 shows the common arrangements for distribution piping. Some arrangements are more common than others.

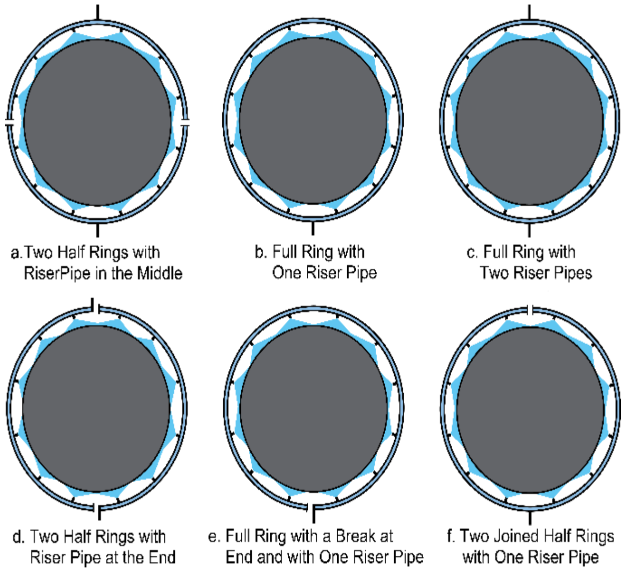

Fig. 2: Cooling System Piping Layout

Layouts b, c, e and f in Fig 2 are not practicable for large diameter tanks due to long pipe runs and large diameters required. Layout “a” in Fig 2 is the preferred method due to efficient resource use. In case layout “a” is not possible layout “b” in Fig 2 can be considered as a replacement.

Water Distribution Methods

There are two major ways to distribute water and select the k-factors for spray nozzles:

1) Average Method: This method uses an averaging strategy to distribute the calculated total water. The method first determines the distance between two spray nozzles based on manufacturer recommendations. Then depending on the distance of distribution ring to tank shell the total number of spray nozzles can be derived. Next the total water application rate is divided by the number of spray nozzles to give the average water discharge of every nozzle. Assuming the minimum required pressure for the hydraulically most remote nozzle i.e. 1.4 bar [11, 15] or higher arbitrary pressure the k-factor can be derived. Then a nozzle with the closest higher k-factor is selected for designing the spray system. This procedure must be carried out for selection of spray nozzles on every level of cooling system distribution rings. Precise calculations and pipe sizing are then carried out based preliminary data and calculations discussed earlier.

Non-uniform application that is the application of water less than and more than what is required at the most remote and nearest nozzles respectively is a drawback of this design method.

2) Linear Density Method: This method employs a novel strategy to choose the K-factors of spray nozzles. It requires changing water density which

most literature is specified as flow rate per unit area for linear density in terms of flow rate per unit length. For storage tanks, the linear application density is the product of surface application rate and the height of shell to be covered. The nozzles linear density can be calculated using the overlapping and non-overlapping length of curtain footprint on the surface to be protected. The spray nozzle with matching or higher linear density is chosen for design.

Case Study of a Typical Cooling System Design

The design of cooling water system for the protection of a one million barrel floating roof tank containing crude oil against non-contacting full surface fire of an adjacent similar tank is carried out. The tanks were spaced according to the NFPA 30 as showed in Fig. 4 [16]. The tanks are identical and their dimensions are illustrated in Fig. 3 and Fig. 4.

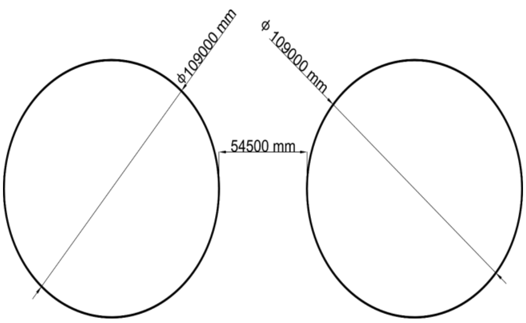

Fig 3: Storage Tank Spacing

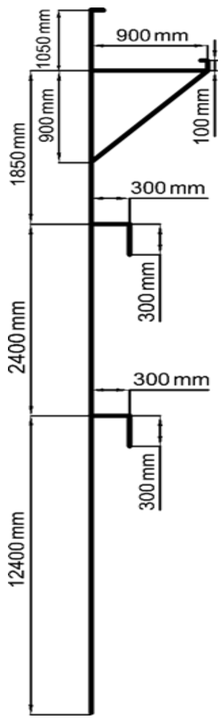

Fig. 4: Tank Geometry

This study assumes that water is applied proportional to incident radiation and the Linear Density Method is used to distribute spray nozzles.

The first step is to evaluate the incident radiation on the tank to be protected. Next the corresponding water film thickness is derived.

Prediction of incident radiation on adjacent tank is carried out using PHAST software. In view of higher safety factor and for the matter of simplicity normal heptane is used to model the pool fire of crude oil [1]. To design for the worst case the tank on fire is assumed to have the highest possible liquid level. The incident radiation is then calculated at different levels of the tank to be protected. The number of levels is arbitrary but can be chosen according to the number of sections created on the tank shell by stiffening rings / wind girders. Based on geometry of the tank in studying four different levels is assumed as showed in Fig. 5.

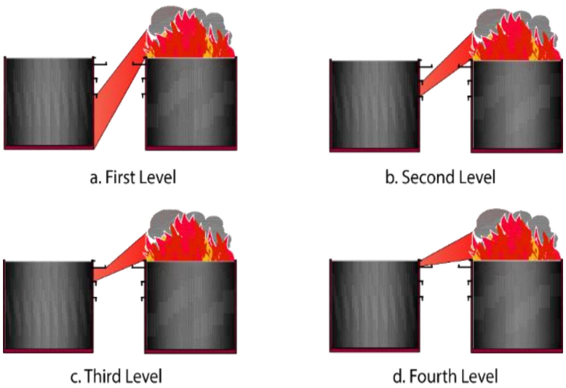

Fig. 5: Tank Levels and Incident Radiation

The incident radiation is calculated for wind speed of 30 m/s and stability of F which are common in southern Iran. The permissible heat flux to the tank is taken to be 8 kW/m2 [8]. The amount of heat to be removed by water is the difference between the incident and permit radiations .

Then the equivalent black body temperature of flame of fire is derived using the Plank's Formula. The maximum radiation flux is taken to be the radiation flux at all radiation frequencies. The absorption of radiation by water film is calculated using Equation 1 and Fig. 6 [7].

Equation 1 Spectral Radiation Absorbtion by Water Film

$$W_{Water,abs,\lambda} = W_{\lambda}\, exp(-\alpha_{\lambda} b)$$

Where

$W_{Water,\ abs,\ \lambda}$: radiation absorbed by water film (W/m^2m)

α_{λ}: frequency dependent absorbtion coefficient

b: water film thickness (m)

The water film thickness is given by Equation 2[7]:

Equation 2 Water Film Thickness

$$b = \left[\frac{2.4\, \acute{M}\, \nu}{\rho\, g w}\right]^{\frac{1}{3}}$$

Where

- b: film thickness (m)
- w: plate width (m)
- $\acute{M}$: overhead water application rate (kg/s)
- ν: water kinematic viscosity (m^2/s)
- g: gravitational acceleration (m/s^2)
- ρ: water density (kg/m^3)

Minimum required water film thickness to absorb the excess amount of heat is calculated using Equation 1. Equation 2 is used to calculate the water density.

Considering a wastage of 2 lit/min/m2 [11, 12], the final values to be used for calculations are derived. The application rates are linear.

Knowing water application rate and using layout "a" in Fig. 2 to distribute water over the tank surface the cooling system is designed.

The results from this design strategy are then compared to the results from the design that uses the average method and the water application rate recommended by API RP 2030 i.e. 4.1 liters per minute per square meter. Also layout "a" in Fig. 2 is used here to distribute water over the tank surface. PIPENET software is utilized for pipe sizing and hydraulic calculations.

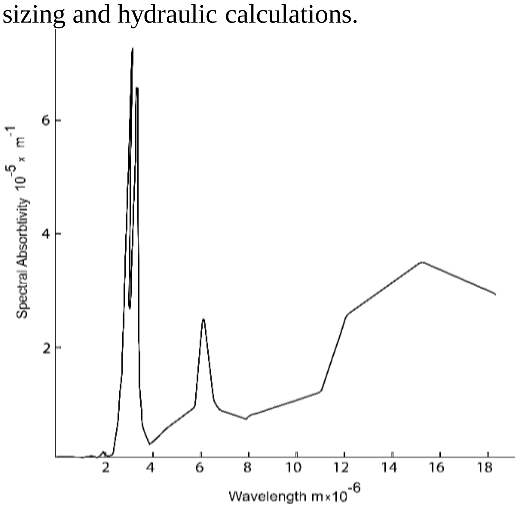

Fig. 6: Absobtion Coefficient

RESULTS

The results of radiation modeling for four levels of tank and for four weather conditions are summarized in table 2.

Selecting the worst weather condition and incident radiation and knowing the permissible incident radiation the amount of radiation is determined and shown in table 3.

Water density to be applied with wastage included is summarized in table 4.

Results for cooling system using Linear Density Method and a water application rate proportionate to incident radiation are summarized in table 5.

The total water demand for half the tank surface is 16553.84 liters per minute at a pressure of 4.32 bars at the bottom of the riser. Total water demand for protection of tank against full surface fire of a similar tank is 33107.68 liters per minute. This system provides protection for shell area above walkway of the tank. Piping system to distribute water on tank surface is shown in Fig. 7. Two similar piping trees are required to cover the entire tank shell.

Table 2: Incident Radiation Modeling

Incident Radiation on Tank to Be Protected (kWm^{-2})

	Height above Ground	Wind Speed:1.5 m/s, Stability F	Wind Speed:1.5 m/s, Stability D	Wind Speed:5 m/s, Stability F	Wind Speed:30m/s, Stability F
Lowest Level	12.4	5.85	5.85	7.45	13.67
Second Lowest Level	14.8	6.17	6.17	8.27	15.16
Second Upper Level	16.65	6.73	6.73	8.91	16.40
Upper Level	17.7	7.04	7.04	9.27	17.13

Table 3: Incident, Permissible and Radiation to Be Absorbed by Water

Level	Total Incident Radiation (kWm^{-2})	Permissible Incident Radiation (kWm^{-2})	Radiation to Be Absorbed by Water (kWm^{-2})
Level 1	13.67	8	5.67
Level 2	15.16	8	7.16
Level 3	16.40	8	8.4
Level 4	17.13	8	9.13

Table 4: Final Linear Water Density

Level	Minimum Water Thickness (mm)	Linear Water Density (lit/min/m)	Final Linear Water Density (lit/min/m)
Level 1	0.22	2.6	27.4
Level 2	0.255	4.05	8.85
Level 3	0.38	13.39	17.09
Level 4	0.45	22.24	24.34

Table 5: Linear Density Method System Design - Operation Summary for Half Ring

Level	Number of Spray Nozzles	True Water Demand (lit/min)	Pressure at Branch (bar)
Level 1	58	5227.18	2.57
Level 2	58	1903.9	2.27
Level 3	58	3342.08	2.06
Level 4	660	6080.66	1.83
Total	834	16553.84	4.32

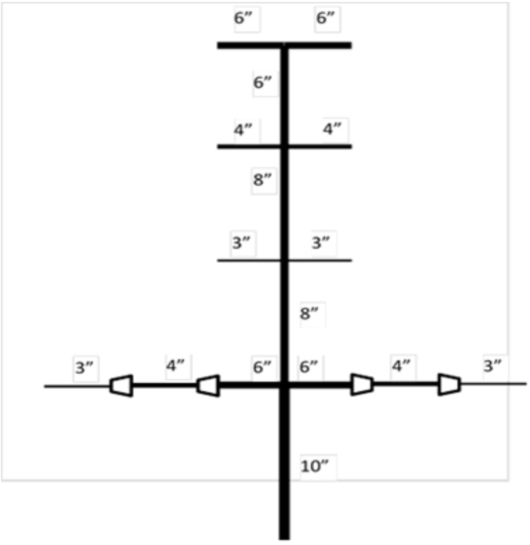

Fig. 7: Piping system to distribute the water

Results for the design that used the recommended water application rate by API RP 2030 and the Average Method are given in table 6. The same piping water requirement and pressure at every level is summarized in table 7.

Table 6: Total Water Demand Using the Average Method

Level	Surface Area (m^2)	Application Density (lit/min/m^2)	Total Water Demand (lit/min)
Level 1	4246.17	4.1	17409.34
Level 2	821.84	4.1	3369.5
Level 3	633.5	4.1	2597.35
Level 4	359.56	4.1	1474.19

Table 7: Average Method Cooling System Design - Operation Summary for Half Ring

Level	Number of Spray Nozzles	True Water Demand (lit/min)	Pressure at Branch (bar)
Level 1	116	10523.42	2.45
Level 2	58	1861.5	2.2
Level 3	58	1970.96	2.02
Level 4	662	1629.72	1.91
Total	894	15985.61	3.84

The total water demand for half the tank surface is 15985.61 liter per minute at a pressure of 3.84 bars at the bottom of riser. Total water demand in this case is 31971.22 liters per minute. This cooling system also provides protection for shell area above walkway of the tank.

DISCUSSION

Results for radiation modeling are shown in table 2. It can be seen that with increasing the wind speed the radiation level from the full surface fire of one tank on any level of the shell of the adjacent similar tank increases. Table 3 demonstrates that at a certain wind speed with height on the target tank increasing the distance increases and hence the quantity of incident radiation also increases. This means higher levels of tank are at higher risk of thermal buckling than lower areas which are backed by observations during many tank fire accidents such as the huge fire at Bayamon oil storage facility, Puerto Rico [33]. Application of water proportional to incident radiation resulted in water films with greater thickness at higher levels compared to lower levels (see table 4). The corresponding linear application density also shows a similar trend. Having assumed a fixed recommended value for water wastage the final linear application density is derived and the trend for it is not increasing from lower levels to higher levels as might be expected. The final linear density for the first level with the highest surface area is greater than the second and third with higher incident radiation as showed in table 4. The reason for it is that the recommended value for wastage is based on surface area which in turn gives higher values for final linear water application density of levels with greater shell area. The water demand for the cooling system design that determines the water application rate proportional to incident radiation and uses the linear density method to apply water consumes 33107.68 liters per minute (refer to table 5). Cooling the area above the walkway requires 36.7% of total water demand while this section constitutes 5.9% of total shell area. In contrast to the first level of the cooling system carries 31.58% of total demand while it constitutes 70% of the shell area. The pressure at the bottom of riser pipe is 4.32 bars which are less than half the available pressure in the fire mains (10 bars).

The method that uses the fixed recommended water application rate is more widely used in projects. Water application rates widely differ from one standard to another as shown in table 1. The water application rate proposed by API RP 2030 is 4.1 liters per minute per square meter [12] and is more common in the oil industry and is therefore used in this study. The total water demand for a cooling system based on the fixed water application rate of 4.1 lit/min/m2 and using the Linear Density method is 31971.22 liters per minute (see table 7). In this method the water application rate is constant and the greater the surface area the higher the total demand. It can be seen in table 6 that despite the fact that the higher levels of the tank receives higher thermal radiation the application rate remains constant and is equal to lower levels that are less exposed. The minimum pressure required

at the bottom of the riser to operate such a system is 3.84 bars (refer to table 7).
Comparing the system that uses the Linear Density Method of water distribution and utilize water application proportional to incident radiation to the design that uses the Average Method and a fixed water application rate of 4.1 liters per minute per square meter shows the former demands 3.55% more water than the latter design. The water demand for level 4 is 3.7 times higher in the Linear Density Method compared to the average method while the demand for the first level in the average method is 2 times higher than the Linear Density Method.

CONCLUSION

It is believed the Linear Density Method is an innovative way to truly protect tanks since it applies water at the density that is really required to protect the tank. The average method distributes water unevenly over the shell surface with higher application at points closer to the riser pipe and lower rates at terminal points of distribution ring. Application of water according to incident radiation allows designing more efficient systems in terms of utilizing resources and the level of protection offered is as required. In contrast designing systems based on recommended values from standards results in a type of protection that is either less or more than what is required.
Installing a cooling ring above the walkway could pose a serious challenge. 79.1% of total number of nozzles used for the system is installed on the highest level of the tank. Installation of larger number of nozzles is costly and thus could be a prohibiting factor. Frequent clogging of nozzles due to small orifice of nozzles is also available. This problem is partly revealed by easy access and frequent maintenance but still such problem make the system high maintenance and diminish the overall reliability and effectiveness of the cooling for the part of shell above the walkway. Limited space above the walkway causes the distribution ring to be installed very close to the shell which in turn causes the number of spray nozzles to increase. It is best to find a way to increase the distance of the distribution ring from the shell or study the possibility of applying water uniformly to the shell without using spray nozzles for instance by drilling holes to the ring pipe in this section.
It is also recommended to further investigate system design and operational parameters for various piping arrangements and tank sizes, to study methods to derive the water application rates based on auto-ignition temperature of the fuel stored.

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