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Analysis of Firefighting and Rescue Circle Model in the Petrochemical Storage Tank Area of Heat-Engine Plant

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Abstract: In this paper, we mainly discussed the model of rescue circle for petroleum storage area, since this is a significantly important issue in daily security. The time radius, resources distribution and importance degree, and foam amount needed, etc. were calculated based on our model. From that comes the reasonable conclusion that the smallest rescue circle radius is that we can extinguish the fire in the center with all the resources within that circle radius. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Firefighting, Rescue circle model, Petrochemical storage.

1. Introduction

The vessels that receive, store and deliver the crude oil, gasoline, kerosene, diesel oil, jet fuel, solvent naphtha, lubricant oil, and heavy oil, etc, can be called petroleum reservoir. It can coordinate the production, processing, and supply of the products, and plays the role of connection. Recently, with the development of economy of the world, especially China, the consumption of petroleum and its derivative products are increasingly used, and therefore the transport is also more and more frequent. To guarantee the daily need of petroleum, the reservoir is becoming larger and larger. On the other side, petroleum is easily flammable, and therefore the measures to prevent fire are urgently and largely needed all around the world.

To understand the danger of petroleum reservoir, we need first list several features that are mostly notable herein [1-3].

i). Easily explosive. Petroleum and its derivative products, under sufficiently high temperature, can vaporize in to the air. When it mixes with the air to an optimum ratio, it can explode when it meets the open fire. In addition, the vessel containing petroleum can also expand itself under high temperature, and this pressure may explode the vessel at end.

ii). High temperature of the flame and highly irradiative. Once upon the fire, the surrounding temperature of it will be extremely high and therefore leading to high radiation. It is reported that at the center of the flame is 1050-1400°C, while the walls of the vessel may be over 1000°C. Additionally, the strength of the heat radiation is proportional to the time length of catching fire. That means, longer time of catching fire will directly result into more destructive radiation.

iii). Fires of large area may be formed. Due to the rapid expansion of the fire of the petroleum, it is easily able to form the fire of large area. The heavy oil will overflow when it catches fire. And sometimes the flame of over 70-80 meters can be formed. And this kind of flame can destroy all stuff that is in the rage of 120 meters. This kind bumping phenomenon can also cause fire around the petroleum reservoir. And the consequence will be seriously bad if there is other reservoir around it.

iv). Expansive character. The petroleum product will expand after being heated. And if the vessel contains too much petroleum or it is closed, this increase of the pressure will lead to the expansion of the vessel, and sometimes even results in fire. That is why we can always see the bulbs at the top or the bottom of the vessel containing petroleum.

v). It can re-catch fire. After the fire of the petroleum or its derivative products, it will re-catch fire once it meets the open fire again, and may also re-explode. That is because after the fire is put out, the walls of the pipeline is still very hot, and if no further measures were taken to lower its temperature, it would continue to cause fire. Therefore, the fire can always re-occur due to the inappropriate guidance or leadership.

In this paper, the model of firefighting and rescue circle is established based on the current conditions of heat-engine plant and its petroleum reservoir. We are aiming at solving the questions of how to distribute corresponding resources, and how much resource is needed to achieve the most cost-effective effect of saving. We in this study mainly focused on the radius of all kinds of fire resources, and optimized it with further hypothesis.

We hope this paper would provide some insights for the following research, and be taken into effect for the rescue of people or other objects in the fire-catching area.

2. Requirements of Extinguishment

2.1. Categories of Storage Tanks

Petrochemical storage tanks are usually used to store all kinds of petroleum and its derivative products. And they can be categorized by the bury depth, construction texture, and structure. They are listed individually in Table 1.

Table 1. Categories of petroleum storage tanks.

storage tank categories	bury depth	Overground	The base of the tanks is equal to or higher than the surrounding designed standard height (in the range of less than 4 meters)
		Underground	The highest level of the liquid in the tanks is 0.2 m lower than the surrounding designed standard height (in the range of less than 4 meters), and the depth of covered soil is no less than 0.5 meter
		Semi-underground	The depth of the storage tank underground is more than half of the total height, and the highest liquid level is less than 3 meters higher of the storage tank (in the range of less than 4 meters)
		Others	Some other tanks are hidden totally underground, in the cave, or artificially caves, etc.
	constructio n texture	Metal tanks	Tanks are made of steel, and connected by welding, and common shapes are standing cylindrical tank, vertical cylindrical tank and special shapes
		Non-metal tanks	Some tanks are made of sticks, rocks and other non-metal materials
	structure	Dome-roof tank	These tanks are localized-roof tanks, and are mainly standing cylindrical tanks. They consist of supported and non-supported tanks. The former one is usually supported by a holder, and the latter one is supported only by the wall, without any holder
		Floating-roof tank	The roof is floating above the liquid, and can fluctuate as the liquid surface fluctuates. Since no air exists in between them, the liquid is hard to evaoprize, and therefore explosive air mixture cannot be formed
		Horizontal tank	Usually they are used in some small petroleum reservoir
		Oil pool	Usually they are made of non-metal materials, and the common shapes are rectangular, square, ellipse. And the depth and area change significantly

2.2. Internal Requirement of Extinguishment for the Storage Tank

Usually, at the first stage of a fire for petroleumchemical storage tanks, a most effective way to help rescue this situation is using the resource from itself, such as automatic fire extinguishing equipment, which is enough to remove the fire. The storage tanks always have some localized or semi-localized foam fire-extinguisher.

At the initial stage of the fire, and before the destruction of the extinguisher, the internal extinguisher should be first used because it can rapidly and accurately help extinguish the fire. Besides, it should be helped with movable foam fire-extinguisher. And it should be noted that the amount of the foam and extinguishing effect should be all right. If the automatic equipment does not work, the extinguishers can be operated manually. For some semi-localized extinguisher equipment, they can be directly connected to the corresponding the fire-pumper.

For the internal extinguisher resources, they are listed as below [3-5].

i. Fire dike. To prevent the overflow of stored substances or the formation of larger fire, the fire dikes are constructed for storage area, including overground and semi-underground storage tanks. The effective volume of the dike is usually equal to or larger than the maximal capacity of the localized tank. And if the tanks are floating roof, the volume should be equal to or larger than half of the maximal capacity of the tank. If there are too many tanks, the internal dikes will be constructed.

ii. Localized foam extinguishing system. Before being destructed by the fire, it should be immediately used, in order to prevent the progressing of the fire. Actually, there are several kinds of foam extinguishers. Low capacity foam extinguisher, usually includes foam producer, mixing pipeline, and foam pump. The amount of the foam is dependent on the area of catching fire. The storage of the foam should meet the need of continuous spraying of 30 min. For medium capacity foam extinguisher, of course, should be more powerful than the former. And besides, the foam amount is larger and quicker. Film-forming fluoroprotein foam fire extinguisher is the most powerful extinguisher, and it is usually used in the case of explosion.

iii. Internal water supply and firehouse. Besides above measurements, water should also be preserved. Firehouse should include water spraying instrument, fire hydrant, water supplying pipeline, water supplying pump and water pool. The spraying valve at the top of the tank is used to lower the temperature of the tank. For the firehouse, according to the law, every petrochemical company should establish one, or uses its nearby fire station, or combines both of them together in order to achieve the best effect.

2.3. External Requirement of Extinguishment for the Storage Tank

In the above analysis, which talks about the internal requirement, they are only effective when they still work. However, once they are destroyed or something goes wrong, the external extinguishing measures need to be supplemented. The key points for the external extinguishing measurements are: foam extinguishing technique, and foam is the main extinguisher; powder extinguishing technique, and powder pulse is best; water spraying technique, and the working pressure of the spraying gun should be around 686 kPa; combination of foam and powder, which means that foam is used first, and then powder is used.

2.3.1. Calculation of Supplied Water Amount

Usually, in the rage of twice of the diameter of the tank catching fire, due to high heat radiation, the contiguous tank may also explode. Therefore in the range of 2.5 times of the diameter, all the tanks should be sprayed with water and cover the tanks. For the tank of heavy oil, it has protection layer. And although cooling water cannot directly work on the walls, it can protect the outer layer from being burned.

The stored water includes water for making foam and cooling water. Furthermore, the cooling water consists of cooling water for tanks catching fire and adjacent tanks, namely:

$$Q = Q_{foam} + Q_{catching} + Q_{adjacent} ,$$

where Q is the total amount of water (L/s), Q_{foam} is the water for making foam, $Q_{catching}$ is the water for cooling tank catching fire, and $Q_{adjacent}$ is the water for cooling the tank adjacent to the tank catching fire.

And Q_{foam} is usually calculated as the following equation.

$$Q_{foam} = 0.94 Q_{mixture} ,$$

where 0.94 stands for the ratio of water in the mixture of foam and water, and $Q_{mixture}$ stands for the total volume of mixture.

Besides, the stored amount of water for making foam should be

$$Q_{storage} = 1.8 Q_{foam} ,$$

where Q_{foam} is the amount of water for making foam, and 1.8 is the extinguishing coefficient, because 1.8=30X60/1000.

For the part of $Q_{catching}$, it should be obtained according to the following equation.

$$Q_{catching} = n\pi Dq ,$$

where n is the number of tanks catching fire, and it is usually one; D is the diameter of the tank catching fire; q is the flux of cooling water.

Similarly, for $Q_{catching}$, there is also stored water, whose amount should be calculated as below.

$$Q = 3.6 T Q_{catching} ,$$

where Q is the stored amount of water for $Q_{catching}$, 3.6 is the coefficient of water flux (1 ton of water is 1000 Liters, and every hour has 3600 seconds, therefore, $L/s=3.6\ t/h$), and T is the time length of cooling.

Finally, we need to get $Q_{adjacent}$, which is as following.

$$Q_{adjacent} = \frac{n\pi Dq}{2} , \quad Q_{adjacent} = n\pi Dq$$

where $Q_{adjacent}$ is the total amount of water for cooling adjacent tank, n is the number of adjacent tanks, and D is the diameter of adjacent tank, q is also water flux as listed in Table 2. As indicated, there are two equations for $Q_{adjacent}$. That is because when movable spraying method is taken, the range of cooling should time 1/2, while the localized instrument should take 1.

Table 2. Water flux of adjacent tanks.

Extinguisher	Tanks		Range of supply	Flux of supply
Movable	Vertical & roof-localized	>1000 m^3	Half of the circumference of the tank	0.6 L/sm
		<1000 m^3	Half of the circumference of the tank	0.35 L/sm
	Horizontal		Half of the area of tank	0.5 L/sm^2
	Underground and semi-underground		Half of the area of uncovered tank	0.1 L/sm^2
Localized	Vertical tank		Half of the circumference of the tank	0.5 L/sm
	Horizontal tank		Half of the area of tank	0.1 L/sm^2

Note: if the adjacent tanks use non-flammable materials, the water flux can reduce to half.

Falling in the same way, the stored amount of water for $Q_{adjacent}$ should be

$$Q = 3.6Q_{adjacent} ,$$

where Q is the total amount of water for storage of $Q_{adjacent}$, 3.6 and T are indicated as above.

2.3.2. Calculation of Supplied Foam Amount

Actually, this part is most complicated, because there are so many kinds of extinguishers and different capacities. This is used particularly the internal fire extinguisher does not work or is destroyed by the fire.

In this paper, we only introduced a quick method of calculation. It is especially suitable for onsite decision, and fits the features of emergency.

$$Q_{mixture} = q \times A \times T$$
$$Q_{foam} = \eta \times Q_{mixture} ,$$

where $Q_{mixture}$ is the amount of the mixture of water and foam, q is the flux of mixture, A is the area of catching fire, T is time length of mixture flux, η is the ratio of water in the mixture.

For example, if 6 % foam mixture is used, and each round lasts for 5 min, the amount for extinguishing certain kind of fire should be

$$Q = 0.06 \times 10 \times A \times 5 = 3A ,$$

where 10 is the mixture flux with the unit of *L/min* m^2, A is the area catching fire.

To be more general, another equation might be used, which is

$$Q = \frac{\alpha}{\beta} TAq ,$$

where Q is the total amount of foam mixture with the unit of Liter, α is the ratio of foam and water in the mixture, β is the foaming coefficient. In this equation, T is period of spraying foam. For each round, it lasts about 5 min, and therefore 6 rounds last 30 min or 1800 seconds. A is the area of catching fire. It is used as estimated from the real condition, or from estimation of the volume of the tank. For example, for metal cylindrical vertical tank, the ratio between volume and liquid area is usually 1000 m^3/113 m^2, 2000 m^3/195 m^2, 3000 m^3/268 m^2, 5000 m^3/407 m^2. q is the flux of foam. For liquid with flash point higher than 60 degrees, q = 0.8 L/s m^2, while for liquid with flash point less than 60 degrees, q = 1 L/s m^2. For fire on the ground, q = 1.2 L/s m^2; for the fire in storage house, q = 1.5 L/s m^2; while for fire on the liquid surface, q = 2 L/s m^2.

3. Dynamic Fire-fighting and Rescue Circle Model

When fire happens, it should be immediately determined that which fire stations should be combined, that is how big is the rescue circle, or the value of diameter of rescue circle. Obviously, this radius is up to the ability of fire-fighting, and the need of capacity to put it out. First, the fire station that is nearest to the fire should join in fire-fighting, and then less nearest, and then on until the fire is put out. In such case, among all the joining stations the distance between the one that is furthest away from the fire and the fire is the radius of fire-fighting and rescue circle.

3.1. Radius of Rescue Circle

This method is based on mathematical model from available empirical equations to get $R=\{r_i\}$, where R is the radius of rescue circle. However, since each petrochemical reservoir should have its own fire-fighting resource, the above equation has to be subtracted from r_{i2}, which is the fire-fighting resource within itself, that is $r_{i1}=r_i-r_{i2}$. There are many factors needed to be taken into consideration, in order to get r_{i1}. For example, the location of tank catching fire, the distance between two tanks, and the importance degree of each resource. Actually, timing R with a factor k is quite a simple way. Hereby, a simplified figure is presented to present the path of obtaining k (shown in Fig. 1). [6-10].

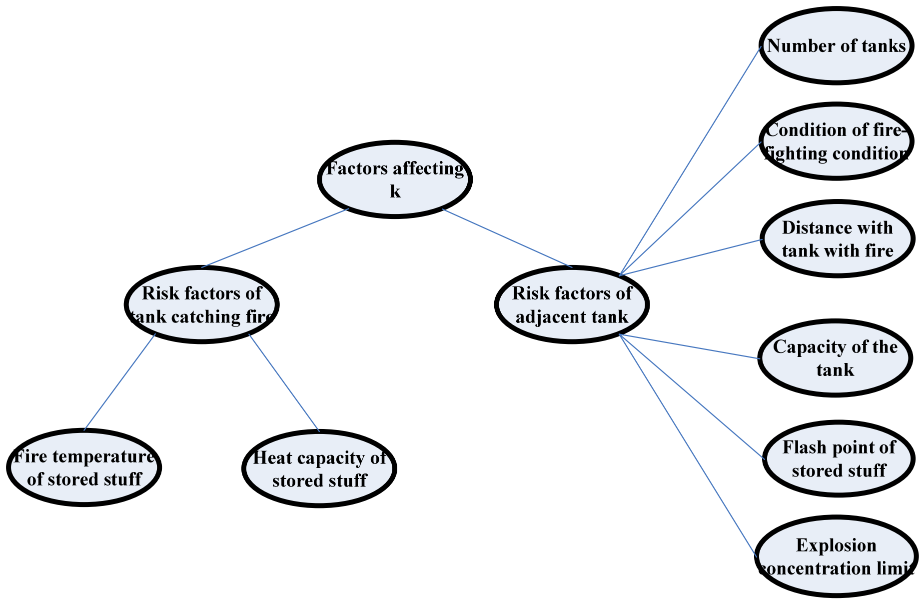

Fig. 1. The determination of value k, by using layered structure instructions.

The ordinary procedure of getting k is as following.

i. Build the sets of evaluation and factors. For example, the factors set $U=\{U_1, U_2, U_3\ldots\ldots\}$, evaluation set V={very large, relatively large, large, medium, relatively small, small}.

ii. The weight of each factor needs to be determined, as shown in Figure 1.

iii. Membership function needs to be determined. Usually, the determination of membership function can use fuzzy statistics, Delphi method or other objective methods.

iv. Finally the fuzzy evaluation matrix R and compound operation need to be processed. There are first-order and second-order fuzzy comprehensive evaluations.

After the overall procedure as indicated above, we can obtain the final rescue circle radius, by saying that the radius of that circle is the maximal value of all the radiuses for various resources, that is

$$T=Max\{t_{ij}\}\ (i=1,2,\ldots,m)$$

And the destination will be $max(min(t_{ij}))$. $min(t_{ij})$ is the minimal radius distance for each resource circle, and $max(min(t_{ij}))$ is the maximal distance among all the minimal radius distances. Therefore, by linear programming, the optimized distance will be obtained.

3.2. Analysis of Applied Resources

In this part, two models will be presented and analyzed, based on dynamic fire-fighting and rescue circle theory, which are actual fire-fighting rescue circle and reinforced fire- fighting rescue circle. This model not only satisfies optimized distribution of resources, but also takes the actual conditions, i.e. enlargement of fire, the wear of fire-fighting equipment, and loss of firemen, in order to achieve dynamic fire-fighting.

Real fire-fighting rescue circle is based on the size of the fire in the tank area, and then the size of the circle will be determined. And the amount of rescue resources will be determined by the number of tanks in threat and their capacities. As the applied resources increase until the fire can be extinguished, the final radius can be determined.

The existing rescue resources should be subtracted when the total resources are determined. And the basic procedure follows Fig. 2 [7].

It's worthy to be noted that, according to the Cannikin Law, it is the most scaring resource that limits the effect of the overall rescuing. As we can see from Fig. 3, the first kind of resource is the most abundant among all these four resources, while the fourth one is the scarcest since the available resource is very far from the site. Therefore, when people are making decision about how much power they need from certain kind of resource, they need to take this into consideration.

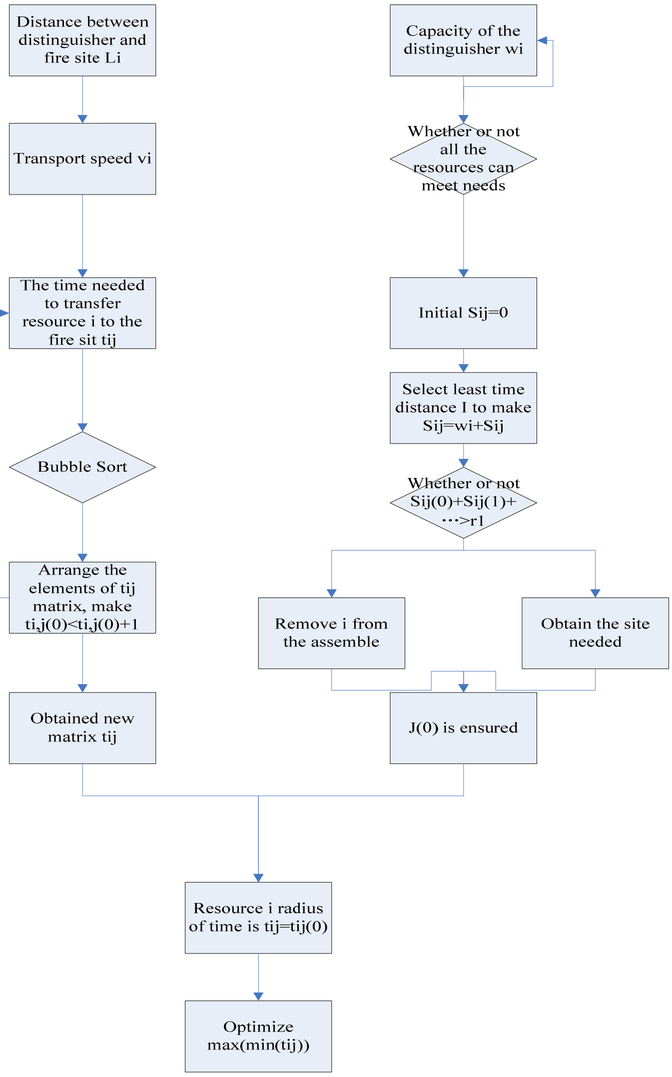

Fig. 2. Calculation method of real fire-fighting rescue circle.

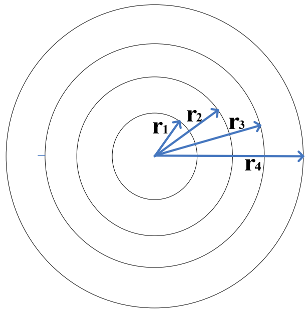

Fig. 3. The simple visualization of radiuses for different resources in the fire extinguishment.

Besides this, we think we also need to take the resource density into account, which nobody has ever thought about. Actually, for some reason, the fire-fighting equipments are not localized into one place, they are instead distributed into several places that are reasonably far away from each other. So, in this case, we should consider this region as a band rich in certain kind of resource. So, in this case, the total number of resources in that band should be expressed in the following format based on first-order Newtonian approximation:

$$r_{tot} = \sum_{i=1}^{n} r_i$$

$$r_i = \rho_i * \Delta S,$$

$$\Delta S \approx 2\pi r \Delta r$$

where r_i is the radius for resource i in the extinguishment of fire. As we can see, $r_1 < r_2 < r_3 < r_4$.

Since nobody has ever cast any sight into this picture, there is going to be a lot of potential to research this area. We may want to designate the area which rich in certain sort of source bonanza. The bonanza may be a round, rectangular, triangle, square, or even any shape. But if people know about the approximate distribution of the fire-fighting resources, they can just calculate the amount of them according to the density as mentioned above. We hope in the future the bonanza may be considered as a basic index for the standard of fire-fighting department investigation.

4. Conclusions

In most cases, when fire occurs in the petroleum storage area, it is hard to extinguish the fire only by the fire forces within that area alone. Therefore, a dynamic circle where nearby resources can be input into that area, is needed. In this paper, the model of dynamic circle was established, resources needed for extinguishment was determined, radius for each resource was calculated. Additionally, we also proposed the way to distribute resources properly, and the problem of inappropriate resource transport was addressed, and therefore a reasonable way to allocate resource scientifically.

i). This study provides two models, i.e. real anti-fire rescue circle and reinforcement anti-fire rescue circle, corresponding to different petroleum storage fire.

ii). The importance degree of storage tank was calculated according to the distance with the tank catching fire and the heat radiation flux, and it suggested that considerable attention should be paid to adjacent storage tanks.

iii). Category different kinds of fire extinguishment resources, and calculate the amount of movable foam needed, in order to meet the real conditions.

iv). Make an arrangement of specific order of extinguishment resources and rescue radius, so that the relative importance can be obtained for each condition, and therefore different resources could be used correspondingly.

However, there are still several aspects that need to be enhanced.

i). Model of resource needed based on risk ranking.

Since in a city there are more than one storage area of petroleum, the calculation of extinguishment resources can be further detailed. For example, based on the risk ranking of each system, the explosion probability and severity can be assessed, and based on that the needed resources are determined and then they can be reasonably allocated.

ii). More accurate calculation of time radius.

In this paper, we only consider that the express is in good condition, and therefore we take the distance as radius into consideration. However, in some cities, the express ways are not that good, and it always takes time to get through the same distances as compared to that in comparatively good express ways. However, what matters in real fire extinguishing is time instead of distance. Therefore, for more accuracy, the time radius can be obtained from mathematical programming based on GIS technique.

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