PASSIVE PROTECTION AGAINST FIRE FOR STRUCTURES AND ELECTRICAL SYSTEMS IN A PETROLEUM REFINING UNIT

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Abstract. *In this work, we study and present alternative solutions for passive protection of structures and electrical systems against fire, in a catalytic cracking unit of a petroleum refinery. The aim of passive protection is to guarantee the integrity of structures subject to fire, during a given period of time, enabling, the necessary procedures to be taken to shut down the unit in a safe way and to control the fire, and thus reducing damage and minimizing the possibility of fire propagation to other areas. Risk analysis techniques were used to identify areas potentially subject to damage to heat radiation. The delimitation of areas where there would be need for passive protection was done using models for flame jets and pool fire usually found in the literature. The dimensioning of passive protection for structures and electric systems using several materials employed commercially for this purpose was estimated using empiric equations. By comparing the results obtained with two methods- numerical solution of the heat conduction equation and use of empirical equations, it was possible to conclude that the use of the empiric equation is slightly less conservative than the results of the heat diffusion equation solved numerically. Using the empiric equation for the cylindrical profiles of steel, the necessary coating to guarantee that the temperature in the interface among the two materials doesn't reach 550°C in two hours it is 13.5 mm for projected mortar, 19.7 mm for* vermiculit*e with* sodium *silicate and 34.5 mm for encasing with concrete protection contour type. The same calculation by numeric method resulted in 15.53 mm for projected mortar, 22.06 mm for* vermiculit*e with* sodium *silicate and 38.98 mm for encasing with concrete protection contour type.*

Keywords*: passive protection, fireproofing, fire, critic temperature, steel*

1. Introduction

Nowadays, one of the principal problems to safety of plants of chemical and/or petrochemical process plants is an accident involving fire in the facilities with potential damage not only the human life, but also the property. Therefore, it is essential to identify the possible sources of fires, as well as the potentially affected areas. It is evident that in industrial units containing hydrocarbons it is a strong priority to have control and proper safety practices in place to reduce the negative impacts of fire accidents.

Usually, fire happens due to an accidental release caused by a leak in tanks, filters, pumps or in any other accessory along pipelines containing flammable material followed by ignition, in some point of the installation.

Accidental fires due to loss of containment of flammable fluids in industrial plants can happen under several forms. For instance, the liberation of a gas or a flammable liquid with immediate ignition usually gives place to a jet fire. When this happens, the direct exposure of other pieces of equipment or structures to the flame or to thermal flux, for a period of time long enough, will cause an increase of the temperature to levels high enough for damage to occur. Another typical situation has to do with damage to equipment or floor support structure, in this case it is said that the damage is indirect, because the collapse of the support structure that is responsible damage to the equipment. Besides the damage to equipment, it is common that fire accidents lead to further loss of containment of flammable material, worsening the situation with amplification of the dimensions of the casualty that, in some cases, can amount to the integral loss of the plant.

The principal constituent elements of an active protection system for open facilities are fire alert systems, fire detection instruments, fire combat agents, systems of water supply, fixed and mobile combat systems. The active protection against fire system of a given installation is only operational when the elements are working and capable to promote the combat to the fire.

Passive systems of protection against fire are preventive systems, because they help to control and to establish safety measures to minimize fire occurrence and to reduce the affected area. Therefore, in general, it can be said that passive protection possesses a great advantage over the active protection due to its lower dependence on equipments as well as on human factors which are both more susceptible to flaws. According to Oliveira (1993), the objective of passive protection is to gain efficiency in combating and avoiding propagation of fire, eliminating several existing contingency factors in the active systems, which are responsible for human and patrimonial losses besides demanding investment

and having high operational costs. Systems of passive protection can be used in several cases, but their use in structural elements to avoid the collapse during fires is the most common.

One of the main methods of passive protection available is the coating of surfaces with fire resistant materials, also known as fireproofing. The advantages of this system are the same already mentioned, the disadvantages are the fact that these materials can facilitate corrosion on the surfaces which they are in contact with, not easily detectable, and there is also the possibility of coating damage due to the action water jets used for fire extinction. Therefore, these materials should possess characteristics that minimize these unfavorable features. Nowadays, the application of these materials is just made in certain priority areas and, therefore, the costs are quite reduced representing, a maximum of 3 to 4% of the equipment or process unit costs.

Another means of passive protection is the use of protection barriers to block or retard fire damage. This way, it is possible to rationalize the use of passive protection for the most important areas of the unit. The best solution for the protection against fire is, usually, a combination of active and passive protection systems. Frequently, passive protection can limit the area where fire will take place and thus time is gained while the material and human resources are mobilized to control the emergency. Therefore, passive protection does not necessarily completely substitute active protection, but it induces a rationalization and/or optimization of the two systems.

2. Identification of accident scenarios and delimitation of vulnerable areas

In order to define which parts of the unit under analysis should be considered for fireproofing, possible accident scenarios were selected using risk analysis standard techniques followed by use of proper models to establish the areas subject to damage. After a brief description of the selected accident scenarios, a review of the physical effects models will be presented.

Six accident scenarios (or initiating events) were selected for estimation of physical effects and delimitation of vulnerable areas, in the FCC (Fluid Catalytic Cracking) unit, five being jet fire and one pool fire (the majority of the involved substances are in the gaseous phase).

For a pipe, the accident could take place any point along its extension, so for delimitation of the area in which equipments could be damaged due to exposure to the jet flames, the length of jet fire was calculated and the area that could be affected was defined by a strip centered in the pipe with a width twice the length of jet. This way, once known the location of leak and calculated the physical effects, that is, the dimension of fire in case of pool fire and the length of jet fire, it is possible to establish which structures could be damaged by fire.

3. Brief description of the models for jet and pool fire

3.1. Jet fire

Typically, a jet fire results from the combustion of flammable material leaking from pressurized equipment. The models of jet fire incorporate many of the same mechanisms considered for pool fire heat radiation fields

The main characteristics of a jet are its length L (distance along the axis of jet to point where the concentration falls below the lower flammability) and diameter D. Characterization of jet is necessary for defining the area that could be touched by flames or exposed to high heat radiation fluxes. The determining factors to define the characteristics of the fire jet are the inner pressure (it establishes the rate of discharge of material) of the equipment and the geometry of the orifice.

According to Mudan and Croce (1988), the geometric characteristics of turbulent jet fires are similar to those of industrial flares. In fact, many of geometric descriptions of flares are based on small scale experiments of jet fires. The models used for calculation, in this work, for jet fire and for pool fire were the same usually used in industrial risk analysis.

3.1.1. Models for calculation of jet fire

3.1.1.1. Discharge of gas

All models to describe turbulent free jets require the rate of gas discharge to the atmosphere. Most of gaseous discharges in process plants are, initially, sonic or critic, where the flow is independent of the downstream conditions. For critical flow, the rate of gaseous mass discharge can be estimated with Eq. (1):

$$m_g = C_d \cdot \psi \cdot \frac{\pi \cdot d^2}{4} \cdot \sqrt{\gamma \cdot \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \cdot \frac{P_r}{\sqrt{\frac{R_g \cdot T_r}{M_g}}} \tag{1}$$

C_d is discharge coefficient, [ad]; d is diameter of hole, [m]; γ is specific heat ratio of the gas, [ad]; P_r is the upstream pressure, usually the pressure of reservoir, [Pa]; m_g is the mass discharge rate, [kg.s^{-1}]; M_g is molecular mass of gas, [kg.kmol^{-1}]; R_g is universal constant of gases, [J.kmol^{-1}.K^{-1}]; T_r is temperature of reservoir, [K]; Ψ is flow factor that has a unitary value for critical flow.

3.1.1.2. Model of Clay et al.

Clay et al. (1988), describe a group of models used by HSE (Health & Safety Executive) for evaluation of risk, where, for LPG (Liquid Petroleum Gas), the fire jet length is given by Eq. (2)

$$L = \frac{\left(\Delta H_c \cdot m_g\right)^{0.444}}{161.66} \tag{2}$$

L is length of jet fire, [m]; ΔH_c is the gas combustion heat, [J.kg^{-1}]

3.1.1.3. Model of Cook, Bahrami and Whitehouse

Cook, Bahrami and Whitehouse (1990), describe a model for fire jet which was incorporated in the software SAFETI (software used by DNV - Det Norsk Veritas for quantitative risk analysis). In this model, the jet is either vertical or horizontal in relation to the ground. The length of the fire jet is evaluated with Eq. (3):

$$L = 0.00632 \cdot \left(\Delta H_c \cdot m_g\right)^{0.478} \tag{3}$$

3.1.1.4. Model of Chamberlain

The model of Chamberlain (1987), for flares take into account parameters such as the geometric effective release diameter, length of free jet in the air, length of fire in other conditions not important in this study. As observed by Moodie and Ewan (1990), when stagnation pressure is sufficiently high, exit speed is sonic and static pressure in exit is larger than atmospheric pressure. The relationship between stagnation and exit pressures is given by the isentropic gas expansion relationship. Equation (4) is used in the Chamberlain model for calculation of maximum length of jet fires.

$$\left(\frac{2.85 \cdot D_s}{L_o \cdot W_g}\right)^{\frac{2}{3}} - 0.2 - 0.024 \cdot \left(\frac{g}{D_s^2 \cdot u_j^2}\right)^{\frac{1}{3}} \cdot L_o = 0 \tag{4}$$

D_s is effective diameter of the source, [m]; L_o is length of jet fire in the vertical direction, [m]; g is acceleration of gravity, [m.s^{-2}]; u_j is the exit speed of the gas, [m.s^{-1}]; W_g is the mass fraction of the gas in stoichiometric mixture with air, [ad].

3.2. Pool fire

Even though pool fires tend to have localized effects, they have a potential for initiating other fires in nearby places or for damaging other pieces of equipment due to thermal radiation fluxes. This type of event takes place as a result of the release of a flammable liquid followed by ignition of the material in the pool. If the material being released is stored as a liquid at a temperature higher than its boiling point, when released a part of it flashes into vapor and the rest forms a liquid pool. As soon as a pool is formed, the evaporation process (or sudden evaporation in case of liquefied gases) can generate a cloud fire followed by a pool fire.

In a pool fire, the predominant factor for damage is the thermal effect, mainly of rate of heat transfer resulting from direct contact with the flames or by heat irradiation for points outside the flame zone. The evaluation of thermal effects depends on fuel kind, pool geometry, duration of fire, location and position of the exposed object, as well as of thermal behavior of the receiver.

Many tests involving pool fire were performed by the American Gas Association – AGA, mainly by Brown, Wesson and Welker (1975). Other tests involving pool fire of natural gas and propane were accomplished by Shell Company where Blackmore, Eyre and Summers (1982), studied the phenomena involving this accident type.

3.2.1. Models of calculation of pool fire

A pool fire is a complicated phenomenon and full theoretical treatment is complex. So, it is appropriate to describe some important empiric characteristics in fire calculation in pool. Evaluation of pool fire is usually accomplished by considering the fire as an irradiating cylinder with height (H) and diameter (D).

3.2.2. Discharge of liquid

The first step for pool fire evaluation is to determine the rate of mass discharge from the system. By simple consideration of the equation of Bernoulli with the introduction of a discharge dimensionless coefficient, C_d (see Crowl and Louvar (1990) and Bird (1978)), Eq. (5) can be established. In general, for liquid flows through a hole with sharp borders, C_d falls between 0.60 and 0.65.

$$m_l = C_d \cdot A \cdot \rho_l \cdot \sqrt{2 \cdot \frac{\left(P_r - P_a\right)}{\rho_l} + 2 \cdot g \cdot \left(h_l - h_0\right)} \qquad (5)$$

A is area of exit hole, [m^2]; ρ_l is specific mass of fluid in [$kg.m^{-3}$]; g is acceleration of gravity, [$m.s^{-2}$]; h_l is liquid height in reservoir, [m]; h_{l0} is initial height of liquid in reservoir, [m]; m_l is rate of liquid discharge [$kg.s^{-1}$].

3.2.3. Mass burning rate

Burgess, Strasser and Grumer (1961), showed that the rate of reduction of the radius of a pool with a diameter larger than a meter is given by Eq. (6)

$$\dot{y}_{max} = 1,27 \cdot 10^{-6} \cdot \frac{\Delta H_c}{\Delta H^*} \qquad (6)$$

$\dot{y}_{max}$ is speed of decrease of pool, [$m.s^{-1}$]; ΔH^* is the modified vaporization heat, [$J.kg^{-1}$].

Modified vaporization heat is the sum of vaporization heat (latent) with an adjustment given by the amount of heat necessary to elevate the temperature of the liquid from ambient to boiling temperature. Based on this, the liquid burning rate per unit of area of pool can be determined by Eq. (7)

$$m_b = \rho_l \cdot \dot{y}_{max} \qquad (7)$$

m_b is the liquid burning rate per unit of area of pool, [$kg.m^{-2}.s^{-1}$].

3.2.4. Maximum diameter of pool

The area for formation of a liquid pool that eventually could suffer ignition was defined by the physical arrangement of the installation. In this work, the confinement area has, approximately, 28 m^2, or a maximum equivalent diameter of 6 meters.

3.2.5. Height of flames in poool fires

Thomas (1963) presents a correlation to determine the height of a turbulent fire, not taking into account the action of the wind, based on experimental data in laboratorial scale. For a circular pool, the correlation is given by Eq. (8)

$$H = 42 \cdot D_{pc} \cdot \left(\frac{m_b}{\rho_a \cdot \sqrt{g \cdot D_{pc}}} \right)^{0,61} \qquad (8)$$

D_{pc} is the equivalent diameter of the circular pool, [m]; H is height of fire, [m]; ρ_a is the atmospheric air specific mass, [$kg.m^{-3}$].

4. Effects of temperature on structures and electric system

Some steel properties of interest such as module of elasticity, coefficient of thermal expansion, specific mass, specific heat and thermal conductivity, among others, depend on the material temperature. Except for specific mass, all other properties are strongly influenced by temperature. According to Silva (1986), the increase of temperature, causes a reduction in mechanical resistance and in rigidity, as well as, the generation of extra additional tensions. Temperature increase results of incorporation of heat by irradiation and/or convection due to temperature differences among hot gases in the fire and components of the object.

Metallic structures, in general, should be protected in case of fire, because structural elements of steel loose about 50% of their mechanical resistance when heated up to a temperature, called critical temperature, of about 550°C. This value of critical temperature can suffer variations depending on amount of chrome present in the steel, size of grains, thickness of the piece and amount of stress.

Elevation of temperature causes an increase in ductility of metals, with is a consequent reduction of mechanical resistance. For some metals, as in the case of steel-carbon, a moderate increase of temperature can also cause a moderate increase in resistance limit. This happens until a certain point from where it begins, soon after, a fast loss of properties.

Other factors can also contribute to a decrease of resistance of metals, such as structural modifications, chemical transformations, reduction of resistance to erosion, etc. Therefore, systems of passive protection should be designed to avoid or to reduce the time of exposure to fire of equipments or structures of steel, so that temperatures never reach critical values.

Electric systems should also be protected against fire, because in case of damage, the safety of installation could be jeopardized due to lack of power to execute the necessary procedures during an emergency situation. Besides, fires in cables and electric spinnings can spread the fire to other parts of installation as well as liberate toxic fumes as a result of the combustion of the wiring insulating material and thus bringing a great risk to people and to facilities.

5. Methods of passive protection

The aim of passive protection is to reduce the rate of heat transfer to an element direct or indirectly exposed to fire without any mechanical, electric or manual interventions. Similarly to active protection, passive protection needs a program of routine inspections for verification of conditions of the system.

The principal types of passive protection commonly used are:

Protection barriers: they are to minimize fire damage and to avoid fire spreading to other areas. The protection barriers are built typically with non flammable materials, as for instance, masonry, concrete or plaster. Use of this type of passive protection is more frequent in constructions, but, occasionally, they are used to separate process units or other operations in that could be in risk of fire. The principal objective of this kind system is to avoid passage of heat or of fires, during a specific period of time, to other areas. Thus, it can be said that the fire will be confined in a certain area facilitating its control.

Insulation with fire resistant materials (fireproofing): Structures of steel when exposed to fire can lose their mechanical resistance and collapse depending on conditions and time of duration of fire. If failure happens, equipments and pipes can break increasing consequences of an accident due to further liberation of flammable material. Insulation with fire resistant materials is the preferred method of fire protection of equipment steel support structures.

Thermal isolation: the thermal isolation of vases and equipments in which there is control of process variables (pressure, temperature, etc.) to attend patterns required by production can be also be useful in protection during a fire.

Safe distances: fire, particularly those that involve hydrocarbons, can generate significant amounts of radiant and convective heat. So, protection against heat radiation in fires is necessary in chemical and petrochemical plants. Distance used as a method of passive protection consists, basically, determining a minimum safe distance so that thermal radiation is kept at low enough levels. Therefore, damage to equipments, electric systems or people can be avoided.

6. Analysis of resistance of structures and electric systems in fire situations

6.1. Empiric equations

According to Milke (1988), many empiric equations relating time of resistance to fire, heating perimeter, thickness of protection among another variables are available to calculate resistance to fire of metallic structures based on data obtained through several tests. Based in empirical data, techniques of adjustment of curves were used in order to establish several correlations.

Empirical correlations can be used to calculate the minimum thickness of thermal insulating material in passive protection to guarantee structural integrity during a pre-established period of time. Tests of standard fire used for determination of these correlations were based on ASTM E-119.

Equations to estimate resistance to fire of metallic columns protected against fire or not, were developed by Jeanes (1980), Stanzak and Lie (1973) and PABCO (1984). The parameter always present in these equations is the quotient W/D, of the lineal specific mass (W) by the perimeter of heating (D) of steel in the protection interface

The parameter that characterizes form of the fire protection system is the heating perimeter, D, expressed in inches, which is defined as the perimeter of the interface structure/protection system. Heating perimeter depends on dimensions of the structural element and of the protection system profile. The larger the value of W in a structural element, the larger will be the lineal specific mass. As the value of heating perimeter gets smaller, the smaller will be the available surface area for heat transfer and therefore the smaller will be the increase in structure temperature.

6.2. Analysis of heat transfer

Analysis with the equation of heat transfer in solids can be used to estimate the time required for the structure to reach its critical temperature. The period of time for the element to reach its critical temperature is also called time of resistance to fire of the element. Critical temperature of a structural element can be based in the criterion of final temperature mentioned in ASTM E-119.

6.2.1. Numerical methods

The use of numerical methods to solve the equation of heat diffusion in solids to calculate the time and spatial variation of temperature in structural element is one of the possible ways to analyze the transfer of heat in structures exposed to fire. In this work, results from the use of a numerical method to solve the equation of heat diffusion in solids were compared to results of insulation thickness found using empiric equations mentioned previously. Solution of this partial differential equation requires one initial and two boundary conditions for each dimension.

Discretization of the heat conduction equation followed Özisik (1994), and a solution was obtained by explicit method in one-dimension for a hollow cylindrical geometry.

As initial condition, it was used a uniform temperature profile to ambient temperature in all points of hollow cylinder (25°C). In the inner surface, $r = R_{int}$, the boundary condition used was insulation, or $\left.\frac{\partial T}{\partial r}\right|_{r=R_{int}} = 0$. In external boundary of cylinder, $r = R_{ext}$, it was considered the transfer of heat by convection and radiation.

7. Procedure for obtaining of results

Now we will list the objective and the procedures that were used to obtain the results which will be presented in section 8:

- To study and to propose passive protection against fire to guarantee the stability of metallic structures and to allow the procedures for emergency control to be executed in a safer way
- To use techniques from risk analysis (Analysis of Vulnerability) to determine more precisely which of the areas of the industrial plant should be protected seeking to rationalize the use of protection method;
- To determine the thickness of the passive protection of structures and electric systems with the use of several materials used commercially based on empiric equations developed by Jeanes, 1980, Stanzak, 1973 and PABCO, 1984, and, for a specific case of a cylindrical pillar the resolution by numeric solution of the equation of heat conduction in solid;
- To analyze which choices of material for passive protection against fire are the most appropriate for each case of the study in function of the thickness, placement form, cost, etc.

8. Results

The results obtained for fire jet lengths led to the conclusion that al equipment inside the unit could potentially be subject to direct flame exposure.

Using empiric equations, for the case of rectangular sections, such as trays of electric cables, the time for the metallic element without fireproofing to reach 550°C was, approximately, 1.17 minutes. It is clear from this result that if metallic element reaches temperature of 550°C in such little time, electric cables will be directly affected almost immediately because the critical temperature for this case is only 70°C. For sections in form of I, this time is 12.35 minutes.

For a cylindrical profile, according to the numerical solution of the heat transfer equation, the time for the temperature in the external border of cylinder without fireproofing to reach 550°C was, approximately, 4.57 minutes and of 2.17 minutes for the temperature of 250°C. Therefore, although the use empiric equations presents less conservative results, the empirical method has the advantage of being simpler to use, at least, in cases of cylindrical profiles.

Based in results just presented for equipment, structural element or electric system when in direct contact with flames or subject to high thermal fluxes, it is possible to see that damage can occur very quickly with consequent compromise to safety of the unit. So, the use of a passive protection against fire in these places becomes very important.

Using the empiric equation for the cylindrical profiles of steel (diameter of 0.1524 m and wall thickness of 0.0254 m), the necessary coating to guarantee that the temperature in the interface among the two materials doesn't reach 550°C in two hours it is 13.5 mm for projected mortar, 19.7 mm for vermiculita with sodium silicate and 34.5 mm for encasing with concrete protection contour type. The same calculation by numeric method resulted in 15.53 mm for projected mortar, 22.06 mm for vermiculita with sodium silicate and 38.98 mm for encasing with concrete protection contour type.

For rectangular profiles only the metallic part of trays for electric cables was evaluated. For protection of the electric cables themselves, use of intumescent ink and of refractory blankets are recommended. Instead of thermal insulation, in many cases the best alternative is simply to relocate the trays for electric cables to places external to the process area. Sometimes, the trays containing electric cables are placed unnecessarily inside the unit. We found a situation where a control panel for of electric cables distribution was located just beside pumps for flammable liquids without any protection barrier (use of panels of plaster, for instance). In case of metallic structures, such as pillars and equipment supports, use of special mortars is recommended to protect these elements against fire and it offer fire resistance.

For new industrial plants, investment costs and, mainly, operational costs of active protection turn out to be equivalent in some process units of the petroleum industry. The operational costs of active protection systems should include personnel and maintenance, equipments, stock of replacement parts, among others. According to Oliveira (1993), the total value of the necessary investment is 6 to 8 times the acquisition cost, assembly and maintenance of a passive protection system, and difference is higher in tanks, equipments and pipes that need thermal isolation. This is so because passive protection due to its insulating and refractory characteristics will not need any other material, what represents a substantial reduction in costs.

9. Conclusions

In this work we studied a catalytic cracking unit of a petroleum refinery in order to determine which is the best strategy for passive fire protection of structures and electric systems. Models of jet fire and pool fire used for delimitation of vulnerable areas were selected among those that present satisfactory results and that are used for calculation of physical effects in modeling of accidents. Recalling all areas could be exposed direct fire, no analysis was done in terms of areas exposed only to thermal fluxes generated by jet or pool fire.

The methods used for evaluation of passive protection against fire in structures were the use of empiric equations and the numeric solution of heat conduction equation for cylindrical geometry. Comparing the results obtained with the two methods, it is possible to conclude that the use of the empiric equation is slightly less conservative than the use of the heat conduction equation. However, the results differ within limits considered acceptable (around 15%) taking into consideration the inherent errors of each calculation method. Needless to say that empiric equation requires only basic mathematical operations.

Based on the material so far presented, it can be conclude that a well projected fire protection passive system, specified correctly and applied in agreement with good engineering practices it is more efficient than active systems which depend on several factors such as maintenance of equipments, pipes and accessories, physical exhaustion of combat teams to emergencies, shortage of water and/or problems with pumping, number of members of brigade of insufficient fire, etc.

Using the empiric equation for the cylindrical profiles of steel, the necessary coating to guarantee that the temperature in the interface among the two materials does not reach 550°C in two hours it is 13.5 mm for projected mortar, 19.7 mm for vermiculite with sodium silicate and 34.5 mm for encasing with concrete protection contour type. The same calculation by numeric method resulted in 15.53 mm for projected mortar, 22.06 mm for vermiculite with sodium silicate and 38.98 mm for encasing with concrete protection contour type.

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